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Defining a zero-carbon building including embodied energy of materials

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The material presented here for examination for the award of a higher degree by research has not been incorporated into a submission for another degree.

Candidates signature..................................

I am the author of this thesis, and the work described therein was carried out by myself personally, with the exception of Chapter 2, Chapter 3 and Chapter 6 where a percentage of the work, as described in the Declaration of Authorship for each of these chapters, was carried out by other researchers.

Candidates signature..................................

An olde saied sawe, itche and ease, can no man please.

Plentie is no deyntie. Ye see not your own ease.

I see, ye can not see the wood for trees.

John Heywood, 1546

A dialogue conteinyng the number in effect of all the prouerbes in the englishe tongue

List of publications

The work reported in this PhD thesis has resulted in three key papers published in international journals. These are listed below and form the content of **Chapter 2**, **Chapter 3** and **Chapter 6**.

Chapter 2

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Chapter 3

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Chapter 6

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List of Abbreviations

CCC	Committee on Climate Change
CI	Carbon Intensity
EC	Embodied Carbon
EE	Embodied Energy
GHGs	Greenhouse gas emissions
Logit()	Log_n(Odds())
MVHR	Mechanical Ventilation with Heat Recovery
OR	Odds Ratio
PE	Primary Energy
PER	Primary Energy Renewable
PH	Passivhaus
PHI	Passive House Institute
PHPP	Passivhaus Planning Package
PV	Photovoltaic array
SBM	Standard Building Model
ZCB	Zero Carbon Building
ZEB	Zero Energy Building
ZeroCC	Zero Climate Change

Summary

A drastic reduction in carbon emissions is needed in the coming decades if the internationally ratified 2°C limit on rising global temperatures is to be met. As the construction and operation of buildings is responsible for nearly one fifth of all carbon emissions globally, improvements in the performance of buildings in this regard could yield significant benefits. There are many compulsory and voluntary environmentally aligned building frameworks that have been developed to bring about such improvements in performance, all with the same goal in mind; to limit (ideally to zero) the impact of buildings on climate change. However, the approaches taken to achieve this and the precise framework definitions vary, resulting in a complex landscape in which compliance with one zero-climate-change-driven building framework does not guarantee automatic compliance with any others. This raises the question of whether all of these building frameworks are equally beneficial with respect to climate change avoidance. Such building frameworks are collectively referred to in this thesis as zero climate change (ZeroCC) frameworks.

Environmental building performance has traditionally been defined in terms of operational energy demand and/or associated carbon emissions, usually measured with reference to a building's floor area. However, many ZeroCC frameworks are criticised for not including in their requirements limits on carbon emissions or energy demand associated with the plug in appliances that are part of a building's operational life. Less criticised is the fact that most ZeroCC frameworks ignore the carbon emissions or energy demand tied to the construction of the building in the first place. The issues surrounding such embodied carbon and energy, and the definition of appropriate metrics to capture this element of a building's performance, are widely discussed at present and a consensus on how to approach these issues is yet to be reached. However, it is clear that embodied carbon and energy are an important part of the performance of a building system as a whole, and are likely to become proportionally more so as operational building performance improves.

Interestingly, there is general agreement within ZeroCC frameworks that energy demand, rather than carbon emissions, should be the metric used to measure building performance. This is despite the fact that it is carbon emissions that drive climate change. It is widely assumed that energy demand is a good proxy for carbon emissions, and therefore many ZeroCC frameworks are designed with a view to improving performance by requiring reduced energy demand per unit floor area. With the development of renewable energy technology, the drive for reduced energy demand has evolved into ideas around net zero energy, and net zero carbon buildings. This necessarily requires building designs to include the often energy and carbon intensive technology needed to generate the renewable energy for offsetting against operational energy demand. As embodied energy and carbon are usually excluded from measures of building performance, renewably generated energy is seen as being free from carbon emissions, and/or free in general.

The inclusion of renewable energy in the assessment of building performance brings further complications. Net zero carbon or energy buildings are often criticised for allowing vast seasonal mismatches in energy demand and renewable energy generation (although an annual balance may be achieved), with little regard for how energy can be usefully stored. In addition, ZeroCC frameworks tend to take the view that grid generated energy (particularly electricity) is carbon intensive, so offsetting even a small amount of grid energy with renewable energy is always beneficial. However, it is clear that energy grids are becoming less carbon intensive in response to climate change concerns, meaning that the climate change mitigation value of renewably generated energy is not static, and is likely to decrease. This suggests that the optimised designs that ZeroCC building frameworks seek to identify inhabit a landscape that is only partially mapped and is in constant flux.

In this research an integrated building carbon and energy model was created to explore this landscape. For the first time, building system performance was measured on the basis of both carbon emissions and energy demand, and included renewable energy generation (via roof-mounted photovoltaics) and embodied carbon and energy measurements. A conceptual building framework was varied element by element and applied to a variety of

domestic building designs. The result was a design space matrix consisting of over 24 million building design-conceptual framework cases each producing an assessed outcome measured in terms of annualised net carbon emissions and net energy demand. A classification tree approach was used to interrogate the design space. The analysis did not seek to identify optimised design choices on the basis of individual building performance. Instead, the analysis made comparisons across the total population of buildings in the design space on the basis of binary building classifications (zero or non-zero energy or carbon). The results show that the zero carbon building design space is almost twice the size of the zero energy design space, and that, while these two spaces currently overlap to some extent, the overlap will shrink in future as energy grids are increasingly decarbonised.

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Chapter 1. Introduction to the thesis

1.1. Overview

In order to mitigate the expected catastrophic effects of rising global temperatures, the global community has targeted capping global temperatures at a maximum of 2°C above pre-industrial levels (United Nations, 2015). To reach this goal will require significant reductions in global greenhouse gas emissions (GHGs) in the coming decades. The global construction industry is well placed to address this challenge in part. The construction and operation of buildings results in significant amounts of GHGs (nearly 20% of global GHGs (IPCC, 2014)), largely as a result of the energy needed to maintain a building's functionality for its occupants, but additionally the energy embodied in the fabric of buildings. Buildings also present potential sites for renewable energy generation if equipped with building integrated (or attached) photovoltaics (BIPV). The design of buildings (shape, material choices, operational characteristics) therefore plays an important role in their lifetime contribution to the global GHG challenge, and their overall impact on changing global temperatures. This PhD work investigated how the integration of building design and building regulation provides the tools with the greatest potential to drive down the GHGs associated with the construction and operation of buildings.

Key term – ZeroCC (Zero Climate Change)

This PhD thesis makes frequent reference to the many building design frameworks that have been developed to reduce the negative impact of construction on climate change. In the literature, such frameworks are variously referred to as low and zero energy and carbon building standards, regulations and assessment methodologies. In the interests of brevity, these concepts will be collectively referred to as ZeroCC (Zero Climate Change) for the remainder of this document.

1.2. Need

Currently energy generation is largely achieved through the combustion of fossil fuels and is responsible for around 65% of global GHGs (IPCC, 2014). By 2050 it is estimated that the global urban population will have grown by around 45% (United Nations, 2014). This will bring an increased demand for buildings, in particular domestic accommodation, and a likely associated increase in energy demand for both the construction and operation of these buildings.

Many parts of the developed world have well defined ZeroCC building frameworks. Given the close association between energy generation and GHGs (often discussed in terms of carbon – CO_2 – emissions) the assumption that reduced energy demand will lead to reduced carbon emissions is perhaps natural. For example, part of the European strategy to reduce carbon emissions is a mandatory requirement that all buildings built from 2021 onwards should be 'nearly zero-energy' with the remaining energy demand satisfied by renewable energy generated on site, or nearby (European Parliament, Council of the European Union, 2010).

However, ZeroCC building frameworks, as they currently exist, do not usually account for actual carbon emissions. In addition, it is rare that they include embodied carbon or energy. This presents two potential problems with the ability of such frameworks to drive building design towards reduced carbon emissions. Firstly, ZeroCC building designs often involve increased use of energy-, and carbon-intensive, materials and technologies to reduce, and/or offset, operational energy demand. If embodied metrics fall outside the scope of what is considered in 'good' building design, there is the potential to encourage the design of buildings whereby energy demand is simply moved from one part of the building lifecycle, where is it measured, to another part, where it is not measured, without any overall improvement in the lifetime energy demand of the building. Secondly, the fuel mix profiles of energy grids across the globe are not uniform and are changing in response to national and international climate change mitigation policies. This means that the climate change impact of renewably generated energy is not the same across the globe and is changing with time. It is therefore not necessarily the case that a building designed to be zero energy actually results in net zero carbon emissions.

1.3. Climate change and carbon emissions

The 2015 Paris Agreement under the United Nations Framework Convention on Climate Change, to which all countries have now agreed, includes an aim to:

> *…reach global peaking of greenhouse gas emissions as soon as possible … and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…*

(United Nations, 2015, Article 4.1)

Although the effect of anthropogenic greenhouse gas emissions on the Earth's climate has long been discussed (National Research Council, 1979), and despite global and national legislative commitments to reduce such emissions (European Parliament, Council of the European Union, 2010; Crown, 2008; United Nations, 1998), these emissions have been continuing to grow in recent years (see Figure 1). In 2014, the Intergovernmental Panel on Climate Change reported that atmospheric concentrations of greenhouse gases were at levels unprecedented in at least 800,000 years, with the global building sector responsible for nearly 20% of emissions (IPCC, 2014).

Carbon dioxide is not the only greenhouse gas, but makes up the largest share (76%), others include methane (CH_4, 16%) and nitrous oxide (N_2O, 6%). In order to allow for these different gases to be accounted for consistently they are measured in terms of Global Warming Potential where CO_2 is given a value of 1 and the other gases are valued according to their relative potency with regard to global warming (e.g. methane = 28, nitrous oxide = 298) (IPCC, 2014). This in turn gives rise to the carbon dioxide equivalent metric (CO_2e) which accounts for all greenhouse gases, in their relative concentrations and with regard to their potency, not just CO_2 specifically.

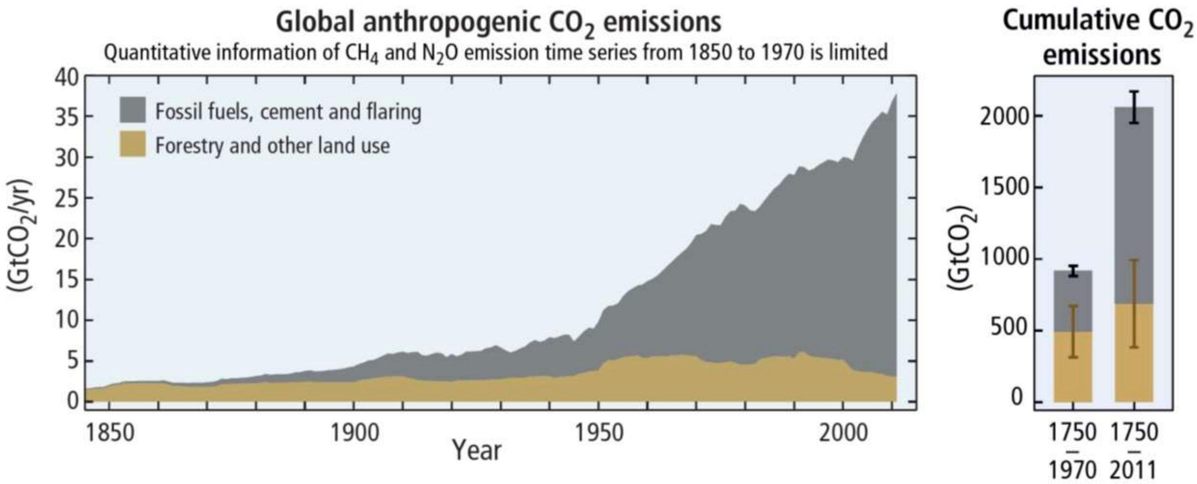


Figure 1: The rise in global anthropogenic CO_2 emissions since approximately 1850 (left). About half of the cumulative anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (right), and cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring have tripled since 1970. Source IPCC, 2014.

Anthropogenic carbon emissions largely result from the combustion of fossil fuels during energy generation (IPCC, 2014), and in the UK, domestic energy use is responsible for over a quarter of all UK carbon emissions (Energy Savings Trust, 2012). The UK's Committee on Climate Change (CCC) – an independent, statutory body established under the Climate Change Act 2008 to advise the UK Government on emissions targets and preparations for climate change (Committee on Climate Change, 2018a) – has recommended that emissions from buildings need to fall by 22% between 2015 and 2030 if buildings are to make the necessary contribution to national carbon reduction targets required under the Paris Agreement (Committee on Climate Change, 2016). However, it is not just the use of energy within buildings that results in emissions. The production of steel and cement alone is reported to account for 44% of UK industrial carbon emissions (Giesekam, et al., 2014). Note that, in Figure 1, cement is highlighted alongside fossil fuel combustion as a particularly significant global source of carbon emissions.

1.4. Energy and carbon emissions

As mentioned above, energy generation and carbon emissions are closely connected, so it is reasonable to assume that reducing energy demand will have the desired effect of reducing carbon emissions. It has been estimated that nearly 20% of the UK's total carbon dioxide emissions in 2017 came from power stations (Department for Business, Energy and Industrial Strategy, 2018). However, UK electricity is generated by a variety of different types of power station (see Figure 2) using different fuels, resulting in different emissions of carbon dioxide per unit of electricity generated. The mix of fuels used to generate UK electricity changes with time, meaning that the carbon intensity (CI) of one unit of UK electricity is not static. Table 1 shows the varying CIs of electricity generated using different fuels, and how the overall CI of the fuel mix has changed over time.

Electricity generation from coal decreased by 70% in the period 2015 – 2017 (Department for Business, Energy and Industrial Strategy, 2018). During the same period, gas generation increased. This shift was driven by an increase in the carbon floor price from £9 to £18 per tonne CO_2 in April 2015. As coal generation is now more expensive than gas (as emissions from coal electricity generation is more than twice that from gas), coal-fired plants tend to reserve generation for periods of highest demand in the winter. This suggests that electricity drawn from the UK electricity grid in winter has a greater impact on climate change than the same amount of electricity drawn in the summer – supporting the idea that renewably generated electricity generated in summer and 'stored' in the grid until winter is not carbon neutral (even if embodied carbon is ignored). Or conversely, the climate change mitigation value of renewably generated electricity is greater in the winter than in the summer.

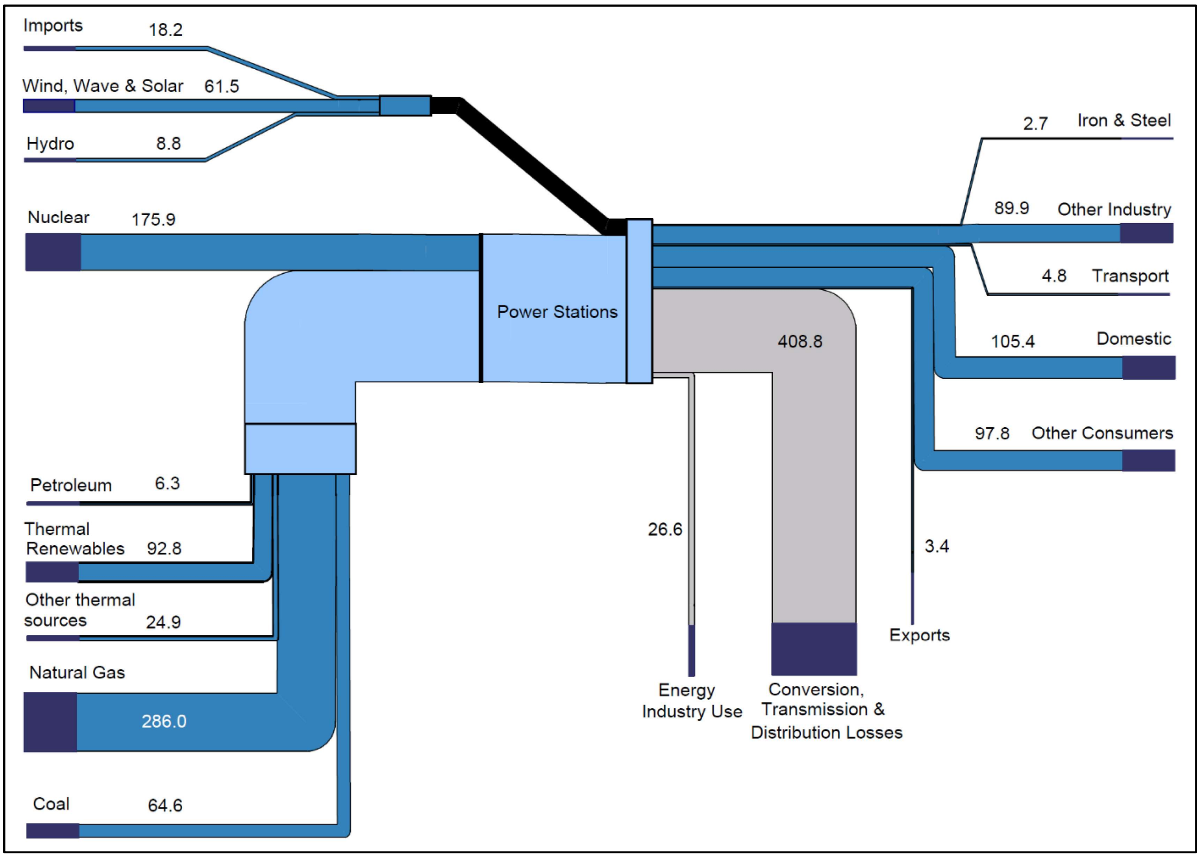


Figure 2: UK electricity flow chart 2017 (TWh). Conversion, Transmission and Distribution Losses is calculated as fuel used minus generation plus losses. Source: Department for Business, Energy and Industrial Strategy (2018).

Table 1: Carbon dioxide emissions from electricity supplied 2015 to 2017. Source: Department for Business, Energy and Industrial Strategy (2018).

Fuel	**Emissions (tonnes CO_2 per GWh electricity supplied)**		
	2015	**2016**	**2017**
Coal	909	931	918
Gas	382	378	357
All fossil fuels	625	497	460
All fuels (including nuclear and renewables)	335	265	225

Most ZeroCC building standards view the national electricity grid as a suitable place to ‘store’ renewably generated electricity. This storage concept assumes that any excess electricity generated in one instant on one site can be fed back into the electricity grid and used instead on another site. The overall result is that the fossil fuels that would have been burnt to supply the second site with electricity remain unburnt, effectively substituting the instantaneous PV electricity for energy that remains stored in fossil fuels. The fossil fuels can then be burnt at another time when PV generation is not sufficient to meet overall demand (e.g. at night). This form of grid storage reduces the fossil fuels being burnt at any one time, but relies on traditional power stations to back up the system. For some, over-reliance on such a system should be penalised in a zero building strategy, and onsite self-sufficiency should be encouraged (Voss & Musall, 2013).

Regardless of how energy is stored, its conversion from a raw resource to a useful energy supply in a building involves losses. The application of primary energy (PE) factors to delivered, or site, energy demand reflects these losses, and to some degree aligns the energy metric with greenhouse gas emissions. For example, the UK PE factor is 3.07 (Department of Energy and Climate Change, 2012). This means that while one tonne of coal contains the equivalent of 8,000 kWh of chemical energy (MacKay, 2009), about 5,400 kWh of this is lost during the coal-to-electricity transformation and delivery to site. Therefore, the primary energy required to supply, for example, a UK factory is approximately three times the electricity demand as measured on site. It should be noted that site generated energy can be translated back into primary energy in a similar way (e.g. PV generated electricity effectively saves three times the amount of primary energy being consumed at the power station). PE factors vary between fuels, which means that the PE factor of a country's national electricity grid depends on the mix of fuels used to generate the electricity. Voss and Musall (2013) provide a number of PE factors for different fuels in different European countries (see Table 2). It should be noted that the UK Government is currently planning to update UK PE factors (and greenhouse gas emissions factors) alongside updating the UK Building Regulations in the near future (Department for Business, Energy & Industrial Strategy, 2017).

Table 2: Primary energy factors for different countries and fuel sources. Data from Voss & Musall (2013).

Fuel Source	Europe	Austria	Denmark	Finland	Germany	Italy	Spain	Sweden
Electricity grid	3.31	1.91	2.50	1.70	3.00	2.18	2.28	1.50
Natural gas	1.36	1.12	1.00	1.00	1.10	1.00	1.07	-
Heating oil	1.35	1.13	1.00	1.00	1.10	1.00	1.12	1.20
Timber	1.06	1.01	1.00	0.50	1.20	0.00	1.25	1.20
Wood pellets	-	1.16	1.00	0.50	1.20	0.00	-	1.20
District heating	-	0.77	1.00	0.70	0.70	-	-	0.90

The use of onsite batteries can be a solution for short-term energy storage. For example, the B10 Haus (also known as Aktivhaus), completed in Stuttgart in July 2014, is designed to generate 200% of the energy it demands (Temperton, 2015). It is a single-story dwelling (85 m^2, including car parking space for an electric car) which includes 40 PV panels on the roof (estimated to generate 8,300 kWh per year) and an 11 kWh lithium-ion battery (see Figure 3). Although the 200% energy goal is impressive the Passive House Institute (PHI) note that it is relatively easy to create a plus energy bungalow given the ratio of useable floor area to the roof area available for PV generation (Krick, 2015). In addition, the financial cost of the technology needed to achieve the 200% goal is high; an estimated £434,500 for the technology (including a hydraulic mixing system that allows different sustainable heating and cooling systems to work together intelligently) compared with £72,400 for the structure of the building (Temperton, 2015).

Figure 3: The B10 Aktivhaus in Stuttgart. Source: Temperton (2015).

As well as a financial cost, battery technology comes with its own carbon and energy costs (see Table 3). It is understood that conventional lithium-ion batteries are reaching their theoretical energy density limit, so research is ongoing into other battery chemistries that may be more cost-effective, such as sodium-ion, or provide higher energy densities, such as lithium-sulphur, in future (NPL, 2017). The embodied profile of batteries can therefore be expected to change over time.

Table 3: Embodied metrics for different types of batteries. Source: McManus (2011)

Battery Type	Embodied emissions (kgCO_2e per kg of battery)
Lead Acid	0.048
Lithium Ion (NMP solvent)	0.066
Lithium Ion (water solvent)	0.173
Nickel Cadmium	0.271
Nickel Metal Hydride	0.096
Sodium Sulphur	0.151

1.5. Delivered energy, primary energy and carbon emissions

The performance of buildings, with respect to climate change, may be assessed on the basis of carbon emissions and/or energy demand. Primary energy is the energy content of natural energy sources such as natural gas, oil or wood. The energy used in buildings is known as delivered, or site, energy. Emission factors (or carbon intensity) describe the carbon emissions generated by the use of one unit of site energy (Voss & Musall, 2013).

Each of these metrics gives an indication of the environmental impact of the operation of a building. However, the metrics describe subtly different things:

- Site energy measurements give a good indication of how efficiently a building uses energy. For example, the Passivhaus building standard places a maximum limit on heat demand of 15 kWh/a per m^2 of internal floor area (Cotterell & Dadeby, 2012), largely dictating the required properties of the building's thermal envelope (given environmental conditions).
- The alternative primary energy metric additionally includes information about the losses incurred in the process of converting raw energy fuels into useable site energy. The outcome of measurements depend on what fuel provides the energy required (see Figure 4). For example, the Passivhaus total primary energy limit (120 kWh/m^2a) places different restrictions on the total site energy demand allowed depending on the heating fuel used – for a building, in Germany, with the same thermal envelope properties, the 15 kWh/m^2a site

energy heating limit consumes nearly 40 % of the total primary energy allowance if electricity is used for heating, but only 14 % if gas is used instead (see Figure 4).

- The carbon emissions metric (not considered in the Passivhaus standard) provides a more direct measure of the impact of a building on climate change – it is a combination of the energy efficiency of the building; the losses inherent in the energy grid that supplies the building; and the carbon emissions arising from generating the energy in the first place.

On a global level, comparisons between building performance that rely on only one of these metrics have the potential to mislead. For example, Figure 4 shows that variability in primary energy factors is not necessarily mirrored in carbon emission factors, and vice versa.

Site energy comparisons show how well buildings perform in terms of energy consumption (in particular heat demand), but do not directly describe carbon emissions. Comparisons on the basis of primary energy give a better indication of the environmental impact of the buildings, but can only make direct comparisons between building performance on site if the same primary energy factors are always applicable (which is not necessarily the case). Likewise, the carbon emissions metric does not allow for direct energy comparisons between buildings connected to different energy grids with different carbon intensities.

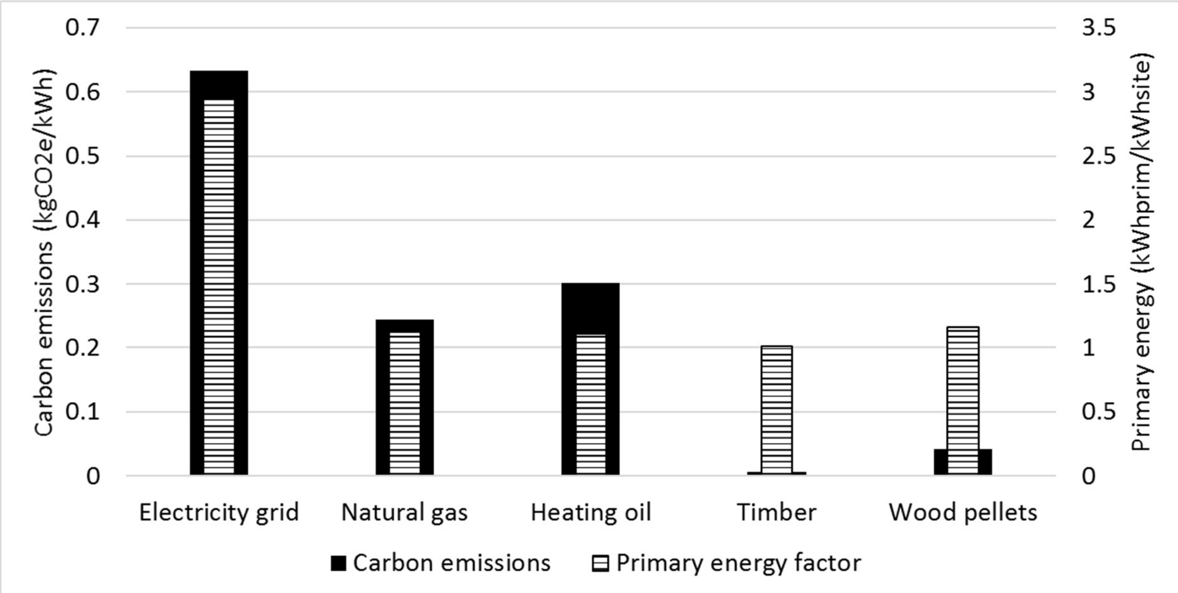


Figure 4: Primary energy factors and carbon emissions associated with different fuel sources in Germany. Source: Voss & Musall (2013).

In developing the new Passivhaus Plus and Premium models, the PHI considered the effect of the aspirational transition of electricity grids to 100% renewable energy (specifically wind and PV). Should such a transition be achieved, the PHI concluded that currently applied electricity PE factors, would no longer be a useful mechanism for the sustainable evaluation of energy efficiency in buildings (Krick, 2015). This is because the normal application of PE factors treats renewable energy as having a PE factor of zero and, based on the assumption that the primary energy of manufacturing renewable energy generation technology can be disregarded, every building connected to a 100% renewable electricity grid would have a primary energy demand for electricity of zero.

The PHI's proposed solution is to start with the assumption that the energy transition has been successful with only renewable energy used, and to account for losses along the energy generation and supply chain in their newly defined Primary Energy Renewable (PER) factors. The PER factors are application specific (e.g. a different factor for each of electricity, hot water, heating), and are calculated to account for losses associated with the different types of storage that are assumed to be necessary for a year-round renewable energy grid as described in Table 4. PER factors do not account for embodied energy – the energy needed to create the energy generation facilities.

Table 4: Efficiencies associated with short- and long-term energy storage methods (Krick, 2015).

Energy storage type	Storage method	Efficiency
Short-term	Pump storage power plants	75 – 80%
Long-term	Hydrogen generation via electrolysis and/or methane generation fed into the natural gas network	40%

Within the PER concept, short-term storage is filled up first in times of over generation and emptied first when demand exceeds supply. For example, some excess summer daytime PV generation will be needed to cover night time demand on a rolling 24-hour basis. Long-term storage is required to provide energy when demand exceeds supply for significant periods of time. For example, some of the excess summer PV generation will be needed to satisfy demand in winter when PV generation is low.

The PHI note that space heating demand occurs mainly in the winter, and so will rely heavily on long-term storage, while domestic electricity demand is relatively constant over the year (as also discussed by Monahan and Powell (2011)), and the demand-supply balance can be regulated using short-term storage more readily. These sources of energy demand are therefore assigned application-dependent PER factors of 1.8 and 1.4 respectively – in this conceptual framework it is assumed that buildings do not have the facilities to store electricity on site (Krick, 2015). In terms of energy generation, electricity generated on site is evaluated with a PER of one.

Taking a different approach to the question of energy storage and generation, Brook and Bradshaw (2014) considered the storage and power generation facilities required to serve the daily energy needs of a developed-world citizen (assumed to be 220 kWh) for 80 years. Table 5 and Table 6 show the calculated greenhouse gas emissions caused by the facilities required to store and generate the energy. Separately, (Stern, 2011) considered how the energy quality composition of energy use has changed over time with the economic development of countries. Energy quality is defined as the relative economic usefulness per heat equivalent unit of different fuels and electricity, which is determined by factors such as energy density; ease of distribution; controllability and amenability to storage. Electricity is described as the highest quality type of energy followed by natural gas, oil, coal, and wood and biofuels. Stern (2011) describes how, during the course of economic development, countries' fuel mixes tend to evolve, and the share of electricity in the total energy use tends to rise.

Table 5 shows a number of different ways energy of different qualities is stored. Natural processes have stored energy in the fuels (coal, gas and uranium) which must be 'burnt' during a one-time operation to release the energy. This operation requires a facility such as a power station, as described in Table 6. Batteries are a different, man-made method of storing energy. They can store and release energy repeatedly, but they can only store energy if it has first been generated by another facility; for example, renewable energy facilities such as PV and wind turbines as described in Table 6. Various combinations of the energy storage methods in Table 5 and the energy generation facilities in Table 6 will allow for the provision of high quality electrical energy. However, no combination excludes the emission of greenhouse gases. This is the case even where renewable energy generation is involved (i.e. PV and wind), although such energy generation is often treated as 'carbon free'.

Table 5: Storage required for 6.4 million kWh – the energy required to service all the lifetime needs of a developed-world citizen (approximately 220 kWh delivered energy per day for 80 years). Unless otherwise stated data sourced from Brook and Bradshaw (2014).

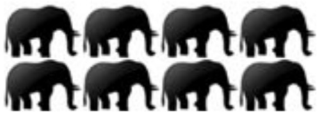
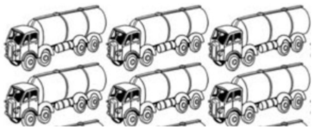
Energy Store	Lifetime storage requirement	Lifetime delivered energy GHGs (CO_2e)	Daily delivered energy GHGs (CO_2e)
Coal	3,200 t  800 elephants' worth	12,000 t Emissions from burning fuel	411 kg
Compressed natural gas (CNG)	1.1 million L  56 x 20,000 L tankers	1,500 t Emissions from burning fuel (based on 0.241 $kgCO_2e/kWh$) (Department of Energy and Climate Change, 2012)	51 kg
Nickel-metal-hydride battery (NiMH)	86,000 t  Batteries to fill the Burj Khalifa service shaft 16 times	8,300 t Emissions to manufacture batteries (based on 0.096 $kgCO_2/kg_{\text{NiMH battery}}$) (McManus, 2011)	0.05 kg Energy generation required Assuming batteries must be able to store 220 kWh daily Assuming battery life of 15 years
Uranium	780 g  41 cm^3 golf-ball sized amount	256 t Emissions from nuclear power (based on 40 gCO_2/kWh including construction, fuel processing and decommissioning) (MacKay, 2009)	8.8 kg

Table 6: Power generation facilities required to generate 220 kWh daily – the energy required to service all the daily needs of a developed-world citizen. Unless otherwise stated data sourced from Brook and Bradshaw (2014).

Power generation Facility	**Carbon footprint of facility (CO_2e)**	**Daily carbon footprint of facility per peson (CO_2e)**	**Carbon footprint of facility over 80 years, including replacement (CO_2e)**
Power station (serves more than one person)	300,000 t (based on 1 GW nuclear power station) (MacKay, 2009)	0.31 kg (based on 1.4 g/kWh from the 25-year life of the 1 GW nuclear power station)	9 t
Solar PV	For PV generation in Accra 71 t (based on annual insolation of 1,799 kWh/m^{2}a in Accra (NASA, 2015) and 474 m^2 PV array required to generate 220 kWh on an average day)	6.5 kg (based on 149 kgCO_2e/m$^2_{PV}$ for PV and 30 year PV lifetime) (Mann, et al., 2014)	190 t Short-term overnight storage required Average daily generation in January = 226 kWh Average daily generation in July = 198 kWh
	For PV generation in Glasgow 131 t (based on annual insolation of 971 kWh/m^{2}a in Glasgow (NASA, 2015) and 879 m^2 PV array required to generate 220 kWh on an average day)	12 kg (based on 149 kgCO_2e/m$^2_{PV}$ for PV and 30 year PV lifetime) (Mann, et al., 2014)	350 t Long-term seasonal storage required Average daily generation in January = 45 kWh Average daily generation in July = 379 kWh
Wind turbine (serves more than one person)	3,700 t (based on wind turbines built in Finland and located in France. Decommissioning includes negative values resulting from recycling) (Tremeac & Meunier, 2009)	3.5 kg (based on electricity generated by a 4.5 MW turbine – 11.7 GWh per year over its 20-year lifetime) (Tremeac & Meunier, 2009)	101 t Storage required

1.6. Aim and objectives

Whether a building achieves a ZeroCC status depends partly on the design of the building (e.g. to reduce energy demand) and partly on the requirements of the ZeroCC standard applied (e.g. what types of energy demand are included). The aim of this thesis is to bring together these two sides of ZeroCC building design to investigate the space within which ZeroCC buildings exist. This research aim was achieved by addressing the following Research Questions (RQ):

RQ 1: What is the state of the global landscape of ZeroCC building standards?

RQ 2: How does the application of a ZeroCC building standard impact design choice?

RQ 3: Does a universally applicable ZeroCC building standard restrict design choice?

1.7. Thesis outline

This PhD work looks at the challenge of defining and achieving a ZeroCC building through the lens of machine learning techniques that are applied in other areas of enquiry. For example, banks make decisions about whether to make loans to customers based on the idea that customers are ‘objects’ with features, the combination of which determine the level of risk associated with the potential transactions (which is either acceptable or not). Similarly, this PhD work views buildings as objects with features which, in combination, determine whether the building can be classed as a ZeroCC building.

This thesis necessarily follows a linear structure, as outlined below. However, the epistemological structure of the contents of this thesis is better described by Figure 5. Chapters 2, 3, 4 and 5 in parallel all identify different features that have played a role in the definition and achievement of ZeroCC buildings previously. The features include both the characteristics of the buildings themselves, and the characteristics of the methods used to assess building compliance. The features identified, and a variety of their possible characteristics, are combined in Chapter 6 generating a dataset of building system objects covering all possible combinations of feature characteristics. Chapter 7 describes in detail the Standard Building Model that was built as part of this PhD work and used to generate the building system object dataset.

This thesis contains three key chapters, each addressing one of the Research Questions, and each based on an international journal publication. **Chapter 2 addresses RQ 1** and presents a review of global ZeroCC building standards. **Chapter 3 addresses RQ 2** and presents the case of a school designed and built to a client-defined zero energy building standard. **Chapter 6 addresses RQ 3** and describes the creation and interrogation of a global ZeroCC design space. Further supplemental, unpublished material is presented around these chapters to provide the context for the PhD work and to explain the development of ideas through the thesis.

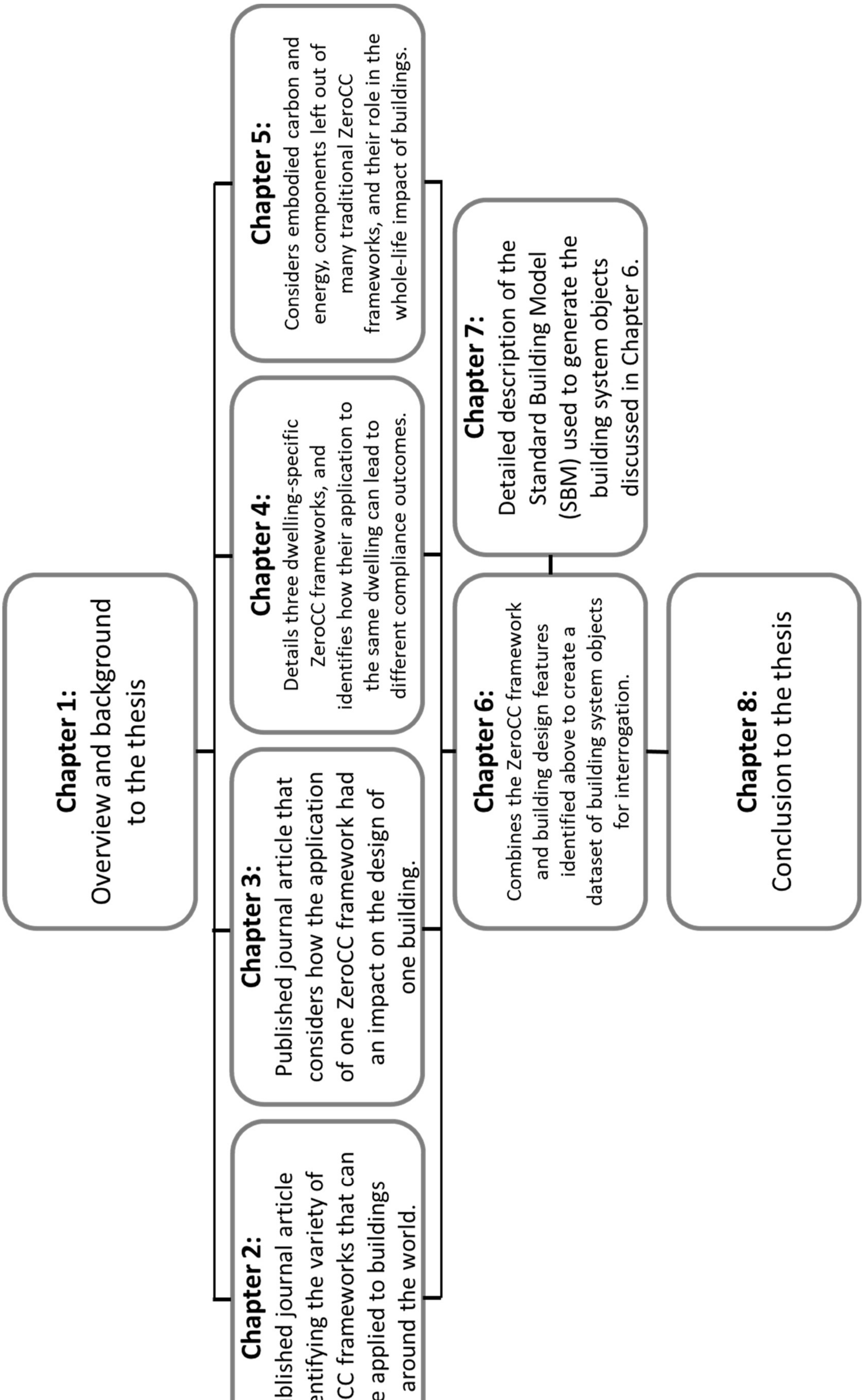


Figure 5: Epistemological structure of the thesis.

The linear structure of the thesis is as follows:

Chapter 1 presents the background and context for this thesis, and describes the links between climate change, carbon emissions and energy demand. Different ways that climate change impact can be measured (delivered and primary energy, as well as carbon emissions) are considered and compared.

Chapter 2 identifies the many different ways the ZeroCC building concept is approached around the world, but also highlights the common themes that are evident. The review of ZeroCC building standards provides evidence of the complications that inhabit the landscape and the need for a globally consistent approach to reducing carbon emissions from buildings. Chapter 2 also considers the importance of global population growth on the need for new buildings, and the effectiveness of current ZeroCC building standards in promoting the construction of new ZeroCC buildings.

In contrast to the complicated ZeroCC landscape uncovered in Chapter 2, **Chapter 3** looks at how ZeroCC concepts can be simplified and applied to a real building. In particular, it describes how the requirements of a client-specified ZeroCC standard dictated the design of a zero energy school. Energy demand and PV generation data collected over a year of monitoring the school in use are also reported. At the end of Chapter 3 a different school, designed to be low embodied carbon, is described and a comparison with the zero-energy school is presented.

Chapter 4 specifically focuses on dwellings as a building type for which there is a large new-build market in the UK, and from which significant carbon emissions result. Three ZeroCC frameworks that are applicable to UK homes are described and a comparison between them is made. Questions arising as a result of this comparison are presented at the end of the Chapter, including how the issue of embodied carbon and embodied energy should be dealt with.

Chapter 5 provides a discussion on the developing subject of embodied energy and carbon in ZeroCC building standards. Although Chapter 2 concludes with the idea that lifecycle issues (i.e. embodied carbon and energy) should be left out of a global ZeroCC building standard, it is evident from the description of the low embodied carbon school at the end of Chapter 3 that the role of embodied carbon can be an important part of ZeroCC design.

Chapter 6 presents the main output of this PhD work. The ideas described in Chapter 6 build on those developed in Chapter 2 and Chapter 3. All the preceding Chapters identify that there are many possible requirements that can be applied to a ZeroCC building, and that ZeroCC requirements applied can profoundly impact the eventual design of a building. In Chapter 6 a variety of potential building designs are combined with a variety of possible ZeroCC requirements in a variety of global locations creating a ZeroCC design space. The space consists of over 24 million design-requirement cases and is interrogated using a classification tree approach. Chapter 6 describes how the design space changes as elements of the building design and/or elements of the ZeroCC requirements change.

The results described in Chapter 6 were generated by a new bespoke ZeroCC building model developed specifically during the PhD. **Chapter 7** provides a detailed description of the bespoke model – the Standard Building Model (SBM).

Chapter 8 concludes this thesis and discusses further work.

Chapter 2. Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard

There are in excess of 70 low or zero energy/carbon building definitions/standards in circulation around the world. However, there are few zero energy or zero carbon buildings. This suggests that despite, or possibly because of, a continuing debate over definitions, aspiration has not been met by reality. In this paper the most important 35 standards are reviewed and a correlation between activity in standard generation and completed buildings is presented. Combining this with the requirement for an 80% cut in carbon emissions, a consideration of the proportion of humanity that live in countries without any standards and the ratio of new-build activity vs. pre-existing stock, leads to a conclusion that there is an urgent need for a binding international zero (rather than low) energy/carbon standard that can be adopted world-wide. It is argued this is only possible if carbon is ignored in favour of energy, and many lifecycle issues put to one side. In part this is because of changing national carbon intensities within the energy supply chain, but it is also due to unresolved issues in carbon and energy accountancy. It is hence suggested that such issues are left to optional additional local standards.

2.1. Preamble

This chapter addresses **Research Question 1** and reports on a review of national and international ZeroCC building standards. The success of these standards in reducing global carbon emissions is considered, and a way forward to achieve a universally applicable zero-energy building standard is proposed.

This Chapter is entirely based on the paper of the same title published in the Journal of Building Engineering in 2016.

2.2. Declaration of Authorship

This declaration concerns the article entitled: Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard	
Status	Published in the Journal of Building Engineering
Details	Williams, J., Mitchell, R., Raicic, V., Vellei, M., Mustard, G., Wismayer, A., Yin, X., Davey, S., Shakil, M., Yang, Y., **Parkin, A**. & Coley, D., 2016. Less is more: a review of low energy standards and the urgent need for an international universal zero energy standard. Journal of Building Engineering, Volume 6, pp. 65-74.
Authors' contribution	The author of this thesis primarily contributed to the review of literature (40%) reported in this paper, in particular on the subjects of embodied energy and carbon and the definition of ZeroCC building standards, and writing the manuscript (80%). The other authors contributed to the review of literature (60% collectively). D. Coley provided overall supervision of this work and edited the manuscript. Each author's exact contribution to the article is outlined below: **A. Parkin**: Formulation of ideas (20%), Review of Literature (40%), Preparation of the manuscript (80%). J. Williams: Formulation of ideas (10%), Review of literature (20%). R. Mitchell: Formulation of ideas (10%), Review of literature (20%) D. Coley: Formulation of ideas (55%), Editing of drafts of the manuscript (20%). V. Raicic, M. Vellei, G. Mustard, A. Wismayer, X. Yin, S. Davey, M. Shakil, Y. Yang: Formulation of ideas (5%), Review of Literature (20%).
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Date and Signature	

2.3. Introduction

The latest IPCC synthesis report (IPCC, 2014) notes that since 1970 cumulative CO2 emissions from global fossil fuel combustion, cement production and flaring have tripled, and that climate change is already having an observable impact on the more vulnerable and exposed parts of the world. This is not only via the occurrence of more extreme weather events but is also from impacts on sensitive natural ecosystems, fishery stocks and the production of crops (IPCC, 2014). Due to the importance of the issue, it has been a longstanding requirement of countries to address their production of greenhouse gasses via the Kyoto and other protocols.

Buildings are a major contributor to world carbon emissions both operationally and during construction, with the energy consumption of buildings being around a third of total energy use worldwide (Srinivasen, et al., 2012). As world population grows and the level of urbanisation increases, the amount of energy required by buildings is also set to increase. The building industry therefore has a key role in helping to reduce carbon emissions by providing buildings that minimise their energy use and general impact. Governments and others have started to rise to this challenge. For example, in the UK the construction and operation of the current building stock accounts for around 30 to 40 per cent of the country's total carbon emissions, and so has been a focus within the Government's overall strategy for reducing emissions (Department for Business, Innovation and Skills, 2010), the policy situation is similar in much of the developed world.

Given the need to cut world carbon emissions by 80% to ensure climate change is limited to a rise of no more than 2-4°C in mean global temperature (IPCC, 2014), all sectors, from transport to electrical generation, to buildings will need to undergo a transformation. Some sectors are likely to find this more difficult than others. With little progress toward non-fossil fuel based aviation having been made, oil still dominating land transport, nuclear power only paying a minor role and the diurnal or seasonal storage of renewable energy proving technologically difficult, several sectors are unlikely to be able to achieve an 80% cut in the required timeframe. Logic therefore dictates that the built environment may well need to offer a greater than 80% cut – quite possibly a 100% reduction to a zero energy/carbon state. By reflecting on the current complexity of the low energy/carbon standards landscape, this paper argues that, to be effective and adopted worldwide, it might be necessary for any zero energy/carbon building standard to be relatively simple.

The concept of buildings that have no energy requirements or are producers of no carbon emissions is therefore an important one, however the details of what a building must achieve to be classed as one of these is still debated. The literature has many examples of definitions of zero carbon or energy buildings (Table 7) and defining what is meant by these terms is often seen as complex and challenging (Pan, 2014; Hui, 2010). Supplementary to these definitions there are in excess of 35 low energy standards in active use across the world. These differ in both their ideology and their methodology, and they use a variety of metrics for verification. Low, rather than zero, energy/carbon buildings have been built in reasonable numbers, however given the need to cut carbon emissions by 80% (IPCC, 2014), the size of the historic building stock and the lack of progress on lowering transport emissions (Department for Business, Innovation and Skills, 2010) it is clear that at least new build needs to be zero energy/carbon.

The future impact of any standard is hard to quantify, as it no doubt depends not only on the standard but also the degree of application it finds. This will vary around the world with the specific demand and levels and nature of construction. For example, a large proportion of the building stock in many countries already exists and so for a standard to find wide use in these areas applicability to retrofit is an important consideration. However, from the data presented later, it would seem the impact has been minor, despite a proliferation of suitable standards.

This work first considers existing definitions of low and zero energy buildings as debated in the literature, their applications, and differences. The review goes on to focus on the currently applied standards, both optional and mandated, around the world and assesses their relation to the definitions regarding the metrics used and the inclusion, or not, of concepts such as embodied energy.

By looking at the proportion of humanity that live in countries without zero carbon/energy standards and the ratio of new-build activity vs. pre-existing stock, the paper argues that there is an urgent need for a simple universal definition of a zero energy building, and that to be practicable it is likely to ignore carbon in favour of energy and not include embodied energy or any lifetime issues. It is then suggested that carbon, embodied energy and lifecycle issues are left to either national standards, or possibly secondary, non-compulsory, additions to the standard rather than be at the heart of the standard.

2.4. Standards

Our ancestors lived in houses that would pass most elements of many of today's low energy/carbon buildings standards. Heat was provided by biomass, lighting from non-fossil oils, domestic hot water heat almost zero, the overall kWh/m^2 consumption very low - mainly due to only heating a very small volume of the building, and accepting very low temperatures in cold climates – or allowing high internal temperatures in hot climates. Electricity use would have been zero. Even with the introduction of coal the consumption would have remained low: 15 kWh/m^2 (the Passivhaus requirement) and a floor area of 200 m^2 implies an annual demand of 3000 kWh. With coal in 1800 selling in London at 28 shillings a ton (Clark & Jacks, 2007) and assuming a calorific value of 5.6kWh/kg, this implies an annual cost of 15 shillings per annum. The daily wage of a craftsman at the time was 37 pennies (Clark & Jacks, 2007), so this implies 5 days labour - a modest amount. However, homes were not built to Passivhaus standards and the efficiency of a coal grate would have been 20% at best. The mean annual UK heating demand (including domestic hot water) is now around 16,000 kWh (Department of Energy and Climate Change, 2015), and a typical boiler efficiency 80%. This implies a typical home in 1800 would have used 11 tons of coal per annum if it had maintained today's typical set point temperatures and hot water use. This is 5 months wages, indicating that lower temperatures were unavoidable, and that fuel poverty is not a new phenomenon. Many around the world still live within such thermal and budgetary constraints.

The modern concept of a building that is self-sufficient is not new, with early concept houses such as the MIT Solar House and the Bliss House from the 1930s and 1950s respectively, representing some of the earliest attempts to meet energy demand with on-site generation (Hernandez & Kenny, 2010). In these cases, the autarkic principle, although not demonstrating complete energy self-sufficiency, was to provide all the space heating requirements by on-site solar throughout the year. Even in these simple early exemplars we see that the concept of zero energy is clearly linked to a set of limiting parameters including the boundary of the site, the space heating demand and the time scale of the balance. From looking at the range of standards now on offer debate about these parameters seems to continue.

Historically, the discussion about the key parameters to use in defining a building as "zero energy", has been wide ranging. A summary by Kibert and Fard (2012) of the definitions of net zero and zero energy buildings arranged in order of appearance and supplemented with additional relevant definitions is shown in Table 7. It is clear that there is a constantly changing landscape and the debate continues. Additionally, Kapsalaki and Leal (2011) for example add a further definition of Zero Energy Buildings (ZEBs) that is more specific about the sources of energy and refers in the definition to a building that does not use fossil fuels but instead gets all of its energy from solar energy and other renewable sources. 2015 saw the introduction of two more Passivhaus standards with very complex energy balance principles lying behind them (Krick, 2015). So it is clear that the landscape of definitions is not a shrinking one. This can cause difficulty for client and architect, as it implies a lack of clarity and can encourage the adoption of the easiest to meet standard, or no standard at all. It is equally likely that this lack of clarity might cause issues for world governments if any standard played a future role in climate negotiations.

Table 7: Summary of zero energy building definitions as presented by Kibert and Fard (2012).

Source	Definition
Esbensen and Korsgaard, 1977	A zero-energy house (ZEH) is considered to be self-sufficient in space heating and hot water supply during normal climate conditions in Denmark.
Gilijamse, 1995	A ZEH is defined as a house where no fossil fuels are consumed, and annual electricity consumption equals annual electricity production. Unlike the autarkic situation, the electricity grid acts as a virtual buffer with annually balanced delivers and returns.
Iqbal, 2004	A ZEH is one that optimally combines commercially available renewable energy technology with the state-of-the-art energy efficiency construction techniques. In a zero-energy home no fossil fuels are consumed and its annual electricity consumption equals annual electricity production. A zero-energy home may or may not be grid-connected. In a zero-energy home annual energy consumption is equal to the annual energy production using one or more of the available renewable energy resources.
Charron, 2005	Homes that utilize solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net zero energy solar homes (ZESH).
Torcellini et al., 2006	A zero-energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable energy technology.
Congressional Research Service, 2007	A net-zero energy (NZE) commercial building is a high-performance commercial building designed, constructed and operated: (1) to require a greatly reduced quantity of energy to operate; (2) to meet the balance of energy needs from sources of energy that do not produce greenhouse gases; (3) to act in a manner that will result in no net emissions of greenhouse gases; and (4) to be economically viable.
Mertz et al., 2007	A net-zero energy home is a home that, over the course of a year, generates the same amount of energy it consumes. A net-zero energy home could generate energy through PV panels, a wind turbine or a biogas generator.
Rosta et al., 2008	A ZEH produces as much energy as it consumes in a year
Laustsen, 2008	Zero net energy buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grid. Seen in these terms, they do not need any fossil fuel for heating, cooling, lighting or other energy uses, although they sometimes draw energy from the grid.
Green Building Advisor, 2010	Net zero-energy buildings (nZEB) are those producing as much energy on an annual basis as it consumes on-site, usually with renewable energy sources such as PV or small-scale wind turbines.
European Parliament, Council of the European Union, 2010	The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.
Aelenei et al., 2010	The nZEB concept can be defined as a building that over a year is neutral meaning that it delivers as much energy to the supply grid as it uses from the grid.

Voss, et al., 2011	The understanding of an nZEB is primarily based on the annual balance between energy demand and energy generation on the building site. An nZEB operates in connection with an energy infrastructure such as the power grid.
Hernandez and Kenny, 2010	A life cycle zero-energy building (LC-ZEB) is one where the primary energy used in the building in operation plus the energy embodied within its constituent materials and systems, including energy generating ones, over the life of the building is equal to or less than the energy produced by its renewable energy systems within the building over their lifetime.
Salom et al. (2011)	A nZEB can be succinctly described as a grid-connected building that generates as much energy as it uses over a year. The 'net zero' balance is attained by applying energy conservation and efficiency measures and by incorporating renewable energy systems.
Sartori et al., 2012	A nZEB is a building with greatly reduced energy demand that can be balanced by an equivalent on-site generation of electricity, or other energy carriers, from renewable sources.
Lund et al. (2011)	A ZEB combines highly energy-efficient building designs, technical systems and equipment to minimize the heating and electricity demand with on-site renewable energy generation typically including a solar hot water production system and a rooftop PV system. A ZEB can be off or on-grid.

Other important standards and proto-standards and supporting materials are those of ASHRAE (ANSI/ASHRAE/IESNA Standard 90.1-1999) and their Vision 2020 document; ISO standards TC163, 205 and 16343; and the European Energy Performance of Buildings Directive.

Following the approach used by Kibert and Fard (2012), we can summarise these definitions in the following equations. The period of balance or comparison can be a month, a year or other time frame, but the shorter the period the more difficult it will be to balance them. If the energy balance is greater than zero in an equation, the result is a net positive energy solution.

(1) Net zero site energy:

$$r_s - m \geq 0$$

where m is the consumption measured by the utility meter; and r_s is the measured renewable energy produced onsite.

(2) Net zero-source energy:

$$r_s - (m + g) \geq 0 \text{ or } r_s - p \geq 0$$

where p is primary energy = $m + g$; and g is the energy losses in the utility system due to energy conversion and transmission.

(3) Near zero energy (EU only):

$$r_{sn} - p \cong 0 \text{ or } r_{sn} - p \rightarrow 0$$

where r_{sn} is the renewable energy produced on-site or nearby by the building owner.

(4) Net zero cost (i.e. the financial value of the energy produced equals that of the required energy. This though does not mean the two balance in energy or carbon units, as they may be from different sources, for example production of electricity but use of natural gas. Being a financial balance the approach might be naturally attractive to building owners.):

$$\$r_{sn} - \$m \geq 0$$

where \$m is the cost of purchased grid-based energy; and $\$r_{sn}$ is the income from the renewable energy produced on-site or nearby by the building owner.

(5) Net zero exergy:

$$\sum \epsilon_{ex} - \sum \epsilon_{im} \geq 0$$

where $\sum \epsilon_{ex}$ is the exergy exported to the grid; and $\sum \epsilon_{im}$ is the exergy imported from the grid

(6) Net-zero carbon:

$$CO_2r - CO_2m \geq 0$$

where CO_2m is the $MtCO_2$ emitted from grid-based energy sources and CO_2r is the $MtCO_{2e}$ avoided by carbon neutral energy sources provided by building owner or utility.

(7) Net zero total energy:

$$r - (p + e) \geq 0$$

where *e* is the embodied energy of building components amortized on an assumed lifetime.

(8) Net zero energy location (net zero total energy plus transportation):

$$r - (p + t) \geq 0 \text{ or } r - (p + t + e) \geq 0$$

where *r* is the renewable energy provided by the building owner or purchased from a utility; and *t* is the commuting energy of building users/occupants.

From Table 7 it is possible to extract some methodical principles:

- The basic units used vary: final energy, primary energy, carbon or finance.
- Connection to the grid might or might not be allowed.
- Energy use is normally calculated over a year.
- The reduction of fossil fuel use can be the focus, rather than the reduction of energy.
- A narrow or broad definition of renewable energy might be included. For instance only building integrated solar technologies might be allowed. Or a wider range of non-local sources might be included.
- There is an emphasis on energy efficiency, but the level required varies.
- The uses of energy that need to be included vary.

The metrics used by any definition are arguably reflective of the ideology, but also may reflect the desire to make a definition more accessible. The main debate here is over the use of carbon verses energy as both have relevance with respect to climate change, energy security and economics. While the use of carbon directly reflects the climate change impact, to assign a value for CO_2 emissions requires one or more conversion factors. The result therefore becomes dependent on the carbon content of any grid energy used and so limits comparison between countries, as the carbon intensity of supply will vary. The range found (see Figure 6) of 0.02kgCO_2/kWh to over 1kgCO_2/kWh shows that a global definition based on carbon emissions would potentially have a different impact on energy use, which would be more onerous for one country compared to another. Hence it would be difficult to get agreement to adopt it as an international standard. Furthermore, the carbon intensity of energy grids around the world is changing rapidly, so there is a methodological problem in calculating the lifetime carbon emissions of any building. This becomes even more difficult if the embodied carbon of redecoration and refurbishment is to be included in the standard.

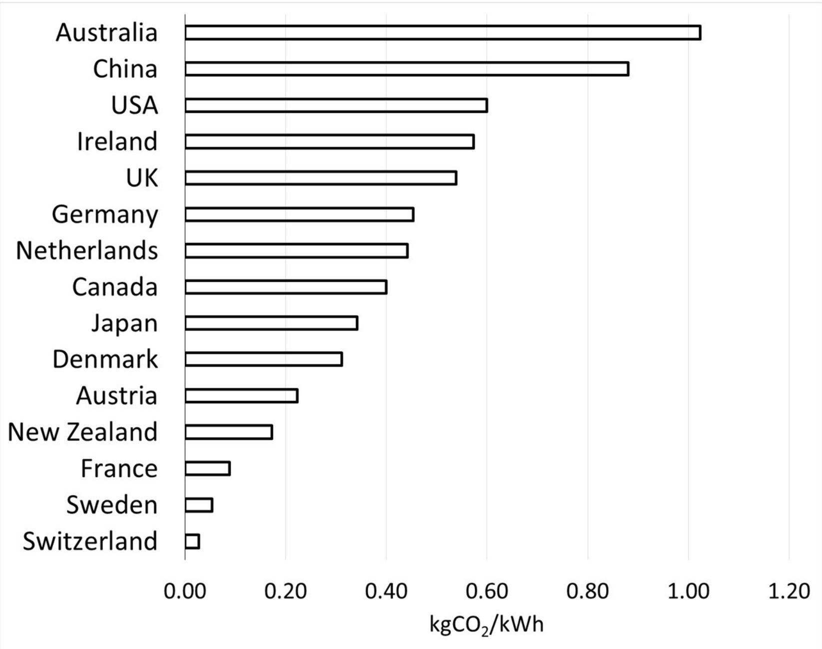


Figure 6: Energy grid carbon intensities in different countries. Data source: PRP Architects (2009).

Final energy, or energy delivered on site, requires no accountancy conversion and so is arguably a clearer, less time or location varying, way of quantifying and comparing the performance of a building and thus may be better as the basis for a global definition. It is however more detached from the original problem and so the use of primary energy is often used instead. This is the energy used at the first point of useful utilisation (Torcellini, et al., 2006), for example the energy burnt at the power station, and while, like CO_2, this will reflect the locality of the building, it is only dependent on the efficiencies of the system and not the carbon content of the fuel source.

Some definitions consider not allowing any fossil fuel use on the basis that even if energy or carbon is accounted for by paying back through the generation of renewable energy, this will not undo the fact that fossil fuels are being used by the building. This approach can be argued against by posing questions about what happens if the owner replaces the biomass boiler, for example, with a gas boiler, because gas is cheaper than wood.

The time scale of the definition is also considered within the literature. If lifecycle analysis is to be included then regardless of the units chosen, a building should repay its embodied content over its operational life, which would be subject to further definition. This is a concept that is gaining significance in most industries but its uptake within the construction industry has been slow; however as the energy efficiency of buildings improves the significance of embodied energy compared to operational energy will change and its relevance increase.

The definition of embodied energy/carbon is itself not straightforward. A variety of methods are used to calculate the embodied metric, and the method used can have a significant impact on the outcome of the calculation. The *process technique* essentially sums the embodied energies of the constituent parts of a building, and is the most common method (Himpe, et al., 2013; Proietti, et al., 2013; Culakova, et al., 2012). It relies on the availability of an accurate and detailed database of materials and components, such as the Inventory of Carbon and Energy (Hammond, et al., 2011), containing data relevant to the supply chain for the building in question. Some argue that this method of assessing embodied energy/carbon is limited as it does not take into consideration energy demands, or carbon emissions, resulting indirectly from the building's construction (Stephan, et al., 2012). For example, while site clearance activities and groundworks are an essential part of a development, their energy/carbon costs are not evident in the fabric of the building. An alternative method is to base calculations on the energy intensities of relevant economic sectors. Acquaye et al. (2011) and Acquaye and Duffy (2010) demonstrate how input-output analysis techniques can be used to determine national energy intensities per monetary unit for various sectors (i.e. how much energy is consumed for each pound spent in that sector). These energy intensities can then be multiplied by the prices of building materials and components to give an estimate of the total embodied energy of the building. While this technique will account for all the direct and indirect energy inputs, its accuracy is limited by aggregation errors, as all components from the same economic sector will have the same energy intensity (Stephan, et al., 2012). On a global, scale further complications will arise due to currency exchange rates. Until a consistent approach to the calculation of embodied energy/carbon is determined, it is difficult to see how this issue could be successfully incorporated into a global zero carbon building standard.

Temporal considerations also arise when a building is defined as net low or zero over a period via the use of a grid connection. For example, does the building need to balance on a daily, monthly or annual basis? Clearly, the shorter the balance period the greater the oversizing of the renewables system will be. This problem is avoided for a standalone, off-grid, building that at no point creates an energy or carbon deficit in its on-site energy use. However, it is likely to be in carbon or energy debt for decades with respect to embodied energy/carbon due to the batteries or other energy store used, so the demand for a standalone solution would seem to be flawed. Also most consider that this is too hard to achieve in a cost or resource effective manner due to the implications of onsite storage. However, if a certain level of energy storage efficiency is achieved in future, such considerations may gain relevance.

The scope of the definition both in terms of what uses of energy are included and what renewables are permitted are also key questions and must be evaluated for a building to meet a particular definition. Performance of any building will also be dependent on the occupants and their use of electricity, including plug loads. This raises the question of at what level a building's responsibility for energy consumption stops? At its simplest level this might be an argument over including unregulated energy (such as plug loads), or not. For example, the UK definition of a zero carbon building does not include unregulated energy. However, as energy efficiency measures increase, unregulated energy use and subsequent emissions become a significant proportion of the energy load and therefore there is an argument that these elements should be included. At a further level of abstraction, there is a clear contradiction in creating a standard that includes the embodied energy of the construction and the energy use of electrical items, but not the embodied energy of those items.

The scope of renewables is also considered in several standards, and this includes a debate over what should be included and whether off-site renewable energy can be considered. For example there are concerns whether off-site input can be consistently counted upon. These debates raise the question of how much of the emphasis of any definition should be on renewable energy generation and how much should be on efficiency savings as a way of minimising the load. At risk here is that under several definitions a building may be energy inefficient but include a large amount of renewable energy. A biomass heated building being a potential example. Heffernan et al. (2013) provide a detailed discussion on a number of zero energy balance issues including which energy uses should be included, the boundaries in relation to energy generation and the timescale of the balance.

2.5. Global Relevance

As previously stated, there are numerous low energy/carbon building standards implemented across the world each using a different definition. Figure 7 analyses the major ones in terms of their core parameters. The 35 standards considered were: OIB, Czech BC, BR10, D3, RT2012, Effinergie, EnEV, DNGB, Passivhaus, Italy NC, Tech. Reg. Construction (Lithuania), Planning and building act (Norway), RCCTE, South Africa BC, CET, Boverket, MukEn, Minergie-A, Minergie-P, Minergie-Eco, Bouwbesluit, Part L, BREEAM, CfSH, IECC, LEED, Canada NEC, LEED Canada, Equilibrium, BEE, ECS (Japan), CASBEE, Australia BC, NatHERS, and H1EE.

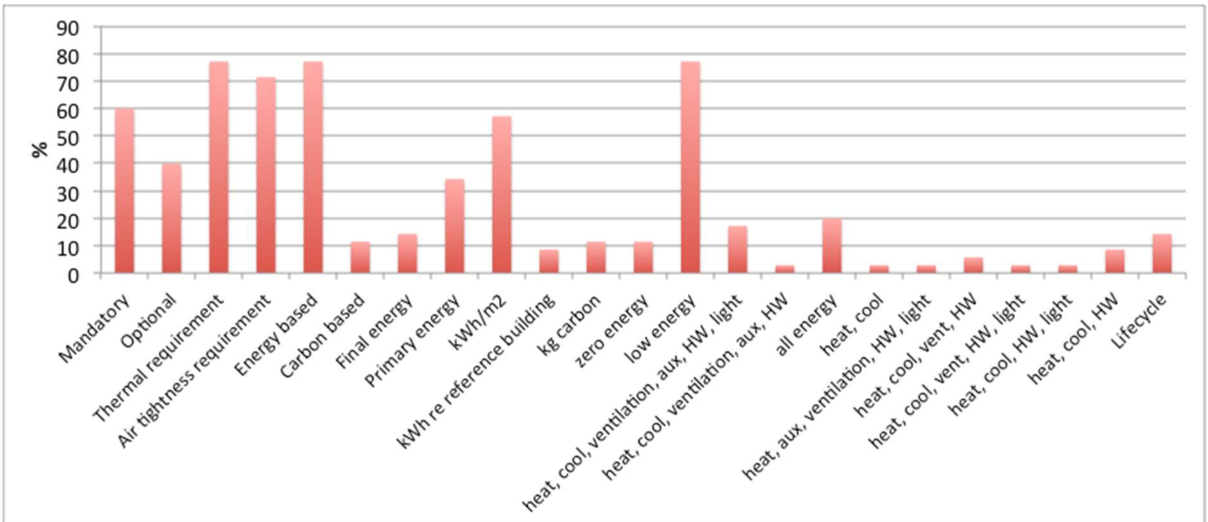


Figure 7: Core parameters of the 35 major low or zero energy building standards around the world presented as the percentage that are presented in terms of each parameter. For example 70% of them have an air tightness requirement. Data taken from Global Buildings Performance Network (2013), International Energy Agency (2014) and PRP Architects (2009).

From Figure 7 we see that fabric thermal performance and airtightness are common features, the use of energy metrics out number carbon ones 7:1, the use of primary energy is common, phrasing the standard in terms of carbon is uncommon, there are 7 times the number of low-energy standards than zero-energy ones, there is great diversity in what energy uses need to be included, and finally, that the use of lifecycle analysis (such as including embodied energy) is rare.

In order to ascertain the impact that standards might be having it is important to consider their locality. This allows the possible impact of a standard to be gauged by comparing its coverage to the global patterns of construction. The geographical coverage of the standards considered in this study are presented in Figure 8, Figure 9 and Figure 10. The number of recorded zero energy buildings in each country is also shown (data taken from the Global Buildings Performance Network (2013), the International Energy Agency BEEP database (International Energy Agency, 2014) and the Zero Carbon Compendium report (PRP Architects, 2009)). Figure 8 shows the number and types (mandatory or optional) of low/zero energy/carbon building standards in place in a number of countries around the world. Figure 9 and Figure 10 show global and regional maps identifying the number of building standards in place in each country along with the respective number of zero energy buildings reported to exist there.

Predictions of the future levels of urbanisation in Asia, Africa and the rest of the world up to 2050 (Figure 11) can be considered as a rough indicator of construction level trends: it is clear that the growth will be in Africa and Asia, yet the zero-energy focus lies elsewhere. Figure 12 shows that there is little correlation between the number of low/zero energy/carbon standards a country has and the number of zero energy buildings built within a country (R^2=0.397). This suggests that having more standards in a country does not imply more penetration and use of a zero energy/carbon standard within that country.

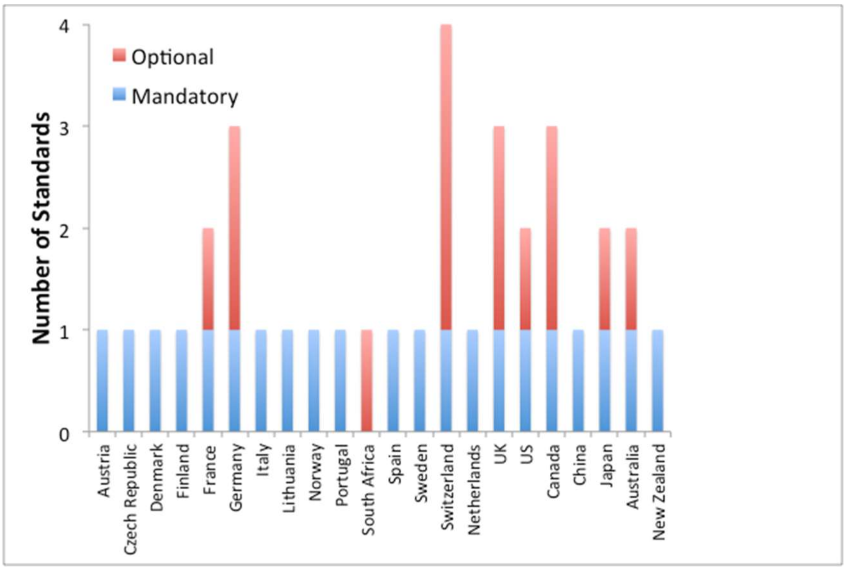


Figure 8: Number of mandatory and optional standards across the world.

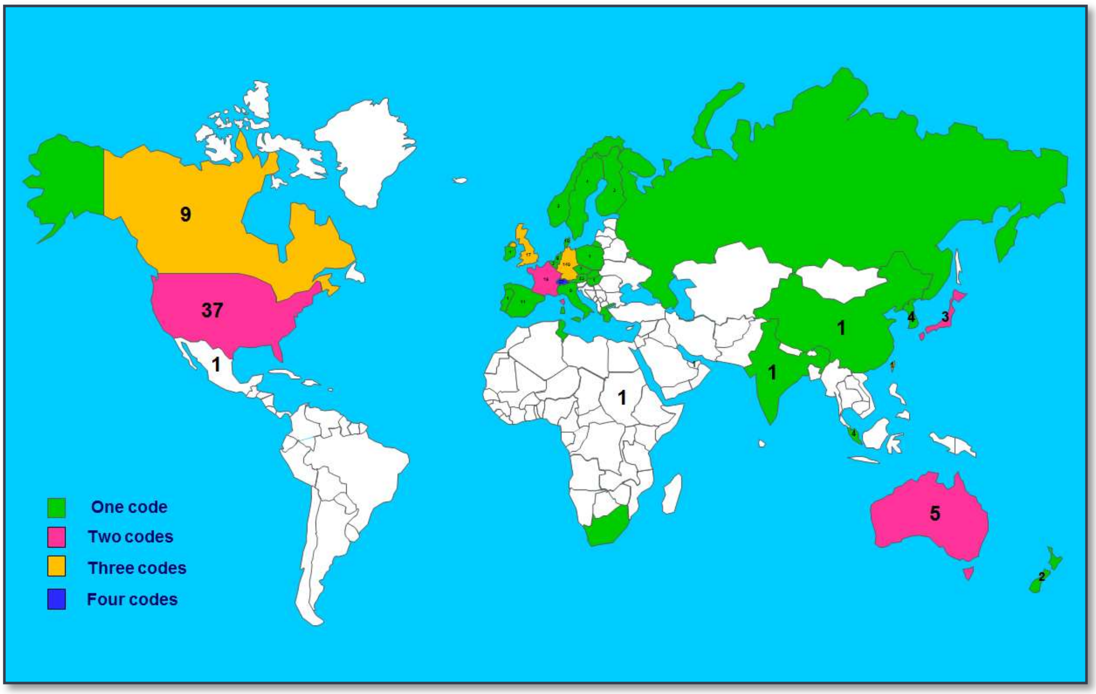


Figure 9: Distribution of building standards and zero energy buildings across the world. The number of low energy buildings is far greater.

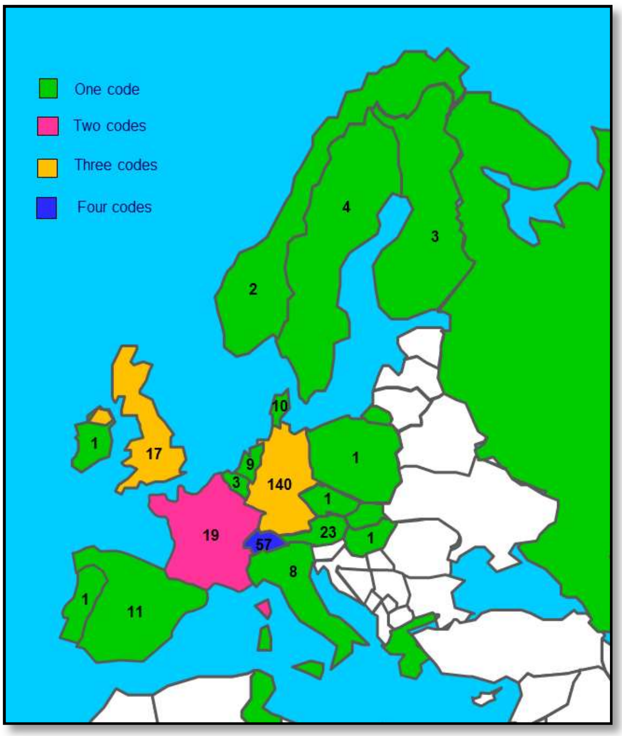


Figure 10: Distribution of building standards and zero energy buildings across Europe. The number of low energy buildings is in the tens of thousands.

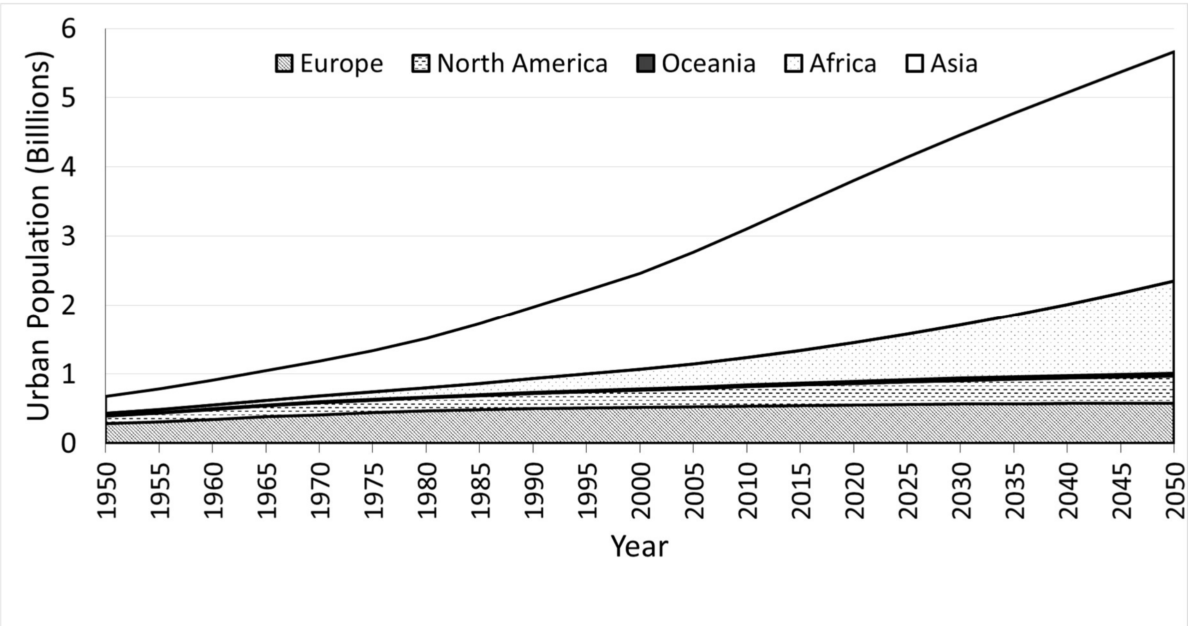


Figure 11: Mid-year urban population estimates by region. It is clear that most growth has for some time been, and will continue to be, outside of regions that have well developed zero energy standards. Data from United Nations (2014).

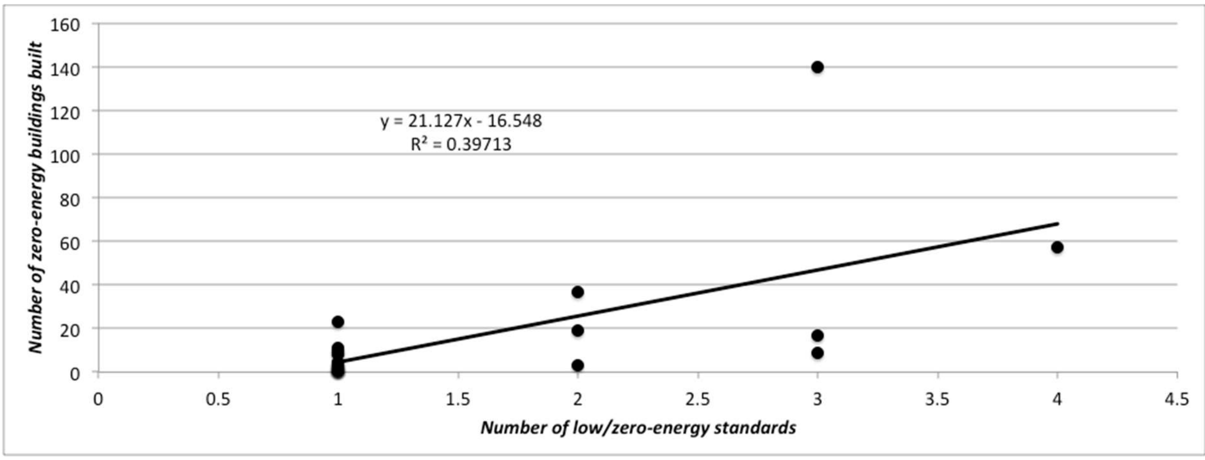


Figure 12: Correlation between number of low/zero-energy standards operational within a country and the number of zero-energy buildings built for the countries shown in Figure 9 and Figure 10. Note the R^2 value is very low, indicating no correlation.

Ireland and Finland's comments in their EU directive compliance plans (Department of Communications, Energy & Natural Resources, 2013; NEEAP, 2014) put forward the view that the regulation of energy use of new buildings may be ineffective in reducing overall energy use if significant numbers of buildings built to less rigorous previous standards still remain. Others have made the same point (Conseil Européen des Professions Immobilières, 2013). As there is no worldwide database of existing building stock, the following uses data from two countries as indicators.

Taking Romania as an example, the allowed primary energy use for new buildings has been reducing over time (Table 8). Assuming these reflect the energy performance of the buildings built at these dates, and the evidence is that (at least for new low energy buildings) buildings typically use more, not less, energy than suggested by the building standard under which they were constructed (Green Construction Board, 2013; CIBSE, 2013), there is a clear need for deep retrofit in order to bring them in line with proposed zero energy standards.

Table 8: Romanian energy standards. Data from Shady and Adina (2015) and Pedro, et al. (2010).

Date	**kWh/m^2**
Before 2005	856
2005-2010	458
2018	333
2020	279
2050-beyond	206

An indication of the way that building quantities can vary over time is seen in data from the Slovak Republic (Table 9). The falling house construction rates possibly show the impact of the global recession, even so, at less than 1 new house per 425 people per annum it is unlikely zero-energy standards for new buildings will have much impact on energy consumption in the built environment, whatever the economic future. We can expect the situation to be similar in much of the world.

Table 9: Slovak house building statistics. Data from Dol and Haffner (2010).

	2007	2008	2009	2010	2011
Number of completed dwellings	16,473	17,184	18,834	17,076	14,608
Number of dwellings started	18,116	28,321	20,325	16,211	12,740

2.6. Analysis

For the above data we can see that:

- there is no shortage of standards;
- these are inconsistent (see Figure 7), with different ones focusing on different goals (carbon or energy), and including different items (all energy use, only regulated energy use, lifecycle energy);
- there is no correlation between the number of standards and building activity or the human population of a country;
- there is no correlation between number of standards and the number of zero-energy buildings (R^2=0.397);
- in future, most buildings will be built in countries with no active zero-energy standard; and
- given the need for an 80% cut in emissions by 2080, the building community has not risen to the challenge of climate change and radical, urgent, world-wide, change is needed.

Whilst there are a wide range of definitions of low and zero carbon and energy buildings, there are certain levels of consensus. Across the standards looked at, thirty of them include a balance to determine a building's performance and the other five relied on prescriptive measures to guarantee a level of performance. Of the metrics used by all the schemes that have an energy/carbon requirement, kWh/m^2 of primary energy was the most common. The UK and Japan are the only major countries using kg of carbon as the defining unit.

Of the standards looked at, only four are for zero rather than low energy. All of the zero targets were from optional schemes. Of the four schemes the most demanding are the top level for the UK Code for Sustainable Homes and Equilibrium. These require a balance covering regulated and non regulated energy use. It is arguable that these two are the closest examples of meeting any of the ZEB definitions fully, however Minergie-P also fulfils the requirements for a ZEB depending on what is encompassed in the balance. The new Passivhaus premium and Passivhaus Plus standards will also be highly demanding in this regard.

One of the most striking points that comes from the data is that all summed the energy use over a year and all allow for grid connection. This is obvious in some respects as the climate a building will experience is cyclical over a year, and studies have shown the cost implications of onsite storage can be large (McManus, 2011), however this may not be so in the future: It will be interesting to see if buildings become both producers and storage facilities rather than just consumers and generators.

The life cycle assessment element within the standards and optional assessments also shows a very clear pattern towards not being regularly applied to real buildings, and this would explain why it is a much more prominent feature in the optional standards, rather than national building codes. However, the true importance of the life cycle impact of products is only now being fully realised, and with more tools and information becoming available accounting for it within building projects will likely increase. However, it is at present unclear how embodied energy/carbon or the general lifecycle of buildings should be treated within a standard. For example, some material choices are likely to lead to designs which need less frequent repair or decoration, but who within the framework of any standard would be able or trusted to make such judgments in a fair, accountable and transparent way? Likewise, the lifetime of some materials is greater than others. For example, concrete rather than lightweight sheeting, but buildings are often torn down before their lifetime has been reached; again, how are such judgments to be made within a standard? For refurbishment, redecoration and maintenance accounting for carbon becomes particularly difficult in a world of changing carbon intensities of supply, and with a global supply chain. For example, how is one to estimate the embodied carbon of paint purchased from an unknown supplier in twenty years' time? The UK-based Integrated Material Profile And Costing Tool (IMPACT) (IMPACT, 2016) is being developed to address these kinds of questions. However, while IMPACT is a method and dataset designed to perform whole building environmental assessment anywhere in the world, it is acknowledged that its UK dataset may not be applicable to materials produced locally in other countries (IMPACT, 2016).

In this study 35 national and independent design standards where considered in detail. Of these 21 are mandatory building standards that are implemented within countries. By cross referencing the two largest free to access databases of building standards (Global Buildings Performance Network, 2013; International Energy Agency, 2014) a further 35, also non-mandatory, regional codes can be identified. Figure 9 indicates that there are very large areas of the world that are not covered by any form of low energy building standard. Most of the rest is covered by a single standard, which is very unlikely to be zero energy. Only a very small proportion of the world is covered by very low or zero energy standards. It is clear that the greatest penetration of low energy standards is in Europe where the majority of countries already have strict national building standards, but even here the delivery of zero energy buildings has been slow.

Looking at construction worldwide, China is responsible for almost half the world's new building activity (Allwood & Cullen, 2012), and if China aspires to Western levels of comfort then this will cause a large increase in resource demand. India has the third largest building sector (the US has the second) and large migration from rural areas, which predominately use biomass, to urban areas which are dependent on oil and electricity – this will further drive increases in energy demand (Jennings, et al., 2011). Therefore, while the focus of defining and constructing low and zero energy buildings tends to be in Western Europe and the US, the majority of new building activity is in rapidly developing economies where these concepts are less well developed and almost never implemented.

The IPCC (2014) argue that '*building standards with strong energy efficiency requirements that are well enforced, tightened over time and made appropriate to local climate and other conditions have been among the most environmentally and cost‐effective ways to decarbonise buildings*'. Given that in many countries the built environment sector is the largest emitter of carbon, it is clear that urgent action is needed. Yet it would appear that zero-energy buildings are nowhere the norm, and in much of the world are non-existent. This is particular so if existing buildings are considered. Maybe we should not be surprised that adoption by governments, clients, or industry has been so slow, and it could be argued that the plethora of definitions discussed above has not helped. It is interesting that the car industry seems to have been far more effective in making progress. One noteworthy non government-directed recent development has been the use of occupant/client led definitions of zero energy building standards (Parkin, et al., 2015). These sidestep issues of national agreement, or buy-in from the construction industry.

It is hence suggested that there is an urgent need for an international focus at the highest level for the creation of a worldwide definition of a low-energy building that can be adopted by all nations.

2.7. Conclusion

Buildings are responsible for 30-40% of final energy consumption and reducing this energy demand would have a significant impact on reducing global carbon emissions. Due to the need for an overall 80% cut in carbon emissions, and indications that some sectors will find it impossible to achieve such a cut, buildings are likely to need to move to a zero energy model. However, there is clearly a very wide range of zero energy/carbon building standards and currently no agreed standard definition which is globally accepted has been suggested; Passivhaus possibly comes the closest to one, but is only a low, not zero, energy standard.

From the worldwide picture of the construction of zero energy buildings, there appears to be no correlation between activity in creating and implementing definitions within building standards and buildings being delivered on the ground. The focus of this activity is Western Europe and outside this region many countries are totally inactive in this regard.

This paper argues that while defining what a zero energy or zero carbon building is can be important and act as a driver for the development of low energy and low carbon buildings, progress in terms of numbers of buildings built has been small and sporadic. Therefore the impact these high performing buildings will have on overall global carbon emissions reduction is limited. The numbers of buildings being developed is relatively small and tends to focus on new build homes in developed economies. These buildings will remain as exemplars to show what is technically feasible, but otherwise their impact can be considered small.

Clearly the approach to defining and delivering significantly increased numbers of zero energy/carbon buildings needs to reflect the different needs in different economies and include different approaches. For example, in countries with the legacy of an older building stock (primarily developed economies), the focus needs to shift to retrofit. Whereas in the emerging economies the focus would be on new build. It is also important to appreciate the need for political will in this ongoing effort; potentially the biggest driving force for, or against, the development of zero energy/carbon buildings. For example, in 2007 the UK Government announced that the top level of the Code for Sustainable Homes would become the domestic zero carbon standard and would be mandatory for all new build homes from 2016 onwards (Department for Communities and Local Government, 2007). However, the burden of financial and industrial concerns led to the gradual relaxing of this mandatory requirement during the following years (Heffernan, et al., 2013; House of Commons, 2015), and, finally, its complete demise in 2015 (Crown, 2015).

Therefore, the focus should be on rapidly agreeing a strong single international building standard applicable to include both new build and refurbishment that encourages national governments to build on this universal definition to include other issues. It is argued that given the difficulty of considering carbon, or embodied energy, these two issues, and others such as transport to and from the building by occupants, electric vehicle charging etc. should not be considered in any such high-level definition and rather left to national or local governments.

This definition will not be easy to create. One stumbling block will be how to deal with time varying building integrated renewables particularly once they form a large fraction of generation. Another will be how to avoid the performance gap, or whether to make the standard based on performance rather than prediction to remove the issue. Hence the research focus needs to shift from an ever-increasing interest in minutiae to thinking about the form of such a pan-world definition. This needs to be of a form that can be applied as rapidly as possible to the world's stock of buildings, and to the new ones that are created as those in poverty gain a first world living standard. There are estimated to be 190 million buildings within the European Union (Rifkin, 2013). This implies that, even if world population does not increase, then a population-proportional estimate suggests that a developed world might expect to need 2.77 billion buildings: All zero energy. If this task is going to be completed within an emission reduction schedule that points to a near zero carbon world in 2080, this implies 43 million buildings need to be built or refurbished to zero energy standards each year. Without this world carbon emissions will remain high.

2.8. Acknowledgements

The authors would like to thank EPSRC for their support via grant EP/L016869/1.

2.9. Postscript

In this Chapter a review of the literature surrounding the concepts of ZeroCC buildings was presented, and a basis for a universal zero-energy building standard identified. It was shown that the global ZeroCC landscape is extensive and varied, and yet the quantity of ZeroCC buildings in existence is still low. It is also evident that there is a lack of alignment between the existence of zero-energy building standards and locations in the world where human populations, and the consequent need for new buildings, is expected to grow most.

In the next Chapter the concept of a zero-energy building standard is explored in more detail. The role that the client and occupants can play in the definition of a zero-energy building is considered, clearly showing that the design space is highly influenced by the form of the ZeroCC standard applied.

Chapter 3. A new way of thinking about environmental building standards: Developing and demonstrating a client-led zero-energy standard

There are over 70 low energy and carbon standards in use around the world. None of these standards have been designed by the clients who pay for and occupy the buildings in question. In this work the client was asked to define the building code via a structured survey. This approach was applied to the design and construction of a new 2 800 m^2 building. The resulting zero-energy standard simply required the building to incur no energy utility bill. One year of monitoring of the completed building was used to see if the standard had been met. The result of this work is a new way of thinking about environmental building standards that solves many of the issues of obtaining and maintaining buy-in from the client.

3.1. Preamble

This Chapter addresses **Research Question 2** and presents a study of the design and monitoring of a building built to a zero-energy standard specified by the client. The resulting standard was performance-based (rather than design-based) and had particular implications for the design of the building. For example, the shape of the building was dictated by the need to accommodate a large enough roof-mounted photovoltaic array to generate sufficient electricity to meet the annual demand of the building. This Chapter also further explores the concept of a zero energy building, including consideration of time periods and frameworks for balancing energy demand against renewable energy generation.

This Chapter is entirely based on the paper of the same title published in Building Services Engineering Research & Technology in 2015.

3.2. Declaration of Authorship

This declaration concerns the article entitled: A new way of thinking about environmental building standards: Developing and demonstrating a client-led zero-energy standard	
Status	Published in Building Services Engineering Research and Technology
Details	**Parkin, A**., Mitchell, A. & Coley, D., 2015. A new way of thinking about environmental building standards: Developing and demonstrating a client-led zero-energy standard. Building Services Engineering Research and Technology, 37(4), pp. 413-430.
Authors' contribution	The author of this thesis has primarily contributed to the review of literature (80%) discussed in this paper, processing and analysis of the data (100%) and writing the manuscript (80%). A. Mitchell and D. Coley collected the data (100%) that is reported in this paper. D. Coley provided overall supervision of the work and edited drafts of the manuscript. Each author's exact contribution to the paper is outlined below: **A. Parkin**: Formulation of ideas (40%), Review of literature (80%), Processing and analysis of data (100%), preparation of the manuscript (80%). D. Coley and A. Mitchell: Formulation of ideas (60%), Review of literature (20%), Design of methodology and collection of data (100%), Editing of drafts of the manuscript (20%).
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Date and Signature	

3.3. Introduction

There are many low and zero-energy and carbon building standards in use around the world. They all have the common aim of reducing the environmental impact of buildings, particularly from the perspective of energy consumption in use. Most of these standards have developed over time with the input of construction industry professionals and experts, and while some are optional others form part of national legislation which governments use to set minimum standards. There are subtle differences between these standards, for example what elements should be included in the determination of a building's energy demand, and whether or not off-site renewable energy production can be used to offset this demand. The design of a building aiming to comply with one particular standard may be quite different to that pursuing an alternative standard, although both may be described as zero-energy or carbon. Where a client wishes to commission a low or zero-energy/carbon building, and has the freedom to choose between standards, it may be difficult for them to comprehend the implications of the differences between such standards and the resulting impact on the design of the building. There is strong potential for a client to end up with a building that does not perform as they expect it to, even though it is deemed to comply with a low/zero-energy/carbon standard. Given the levels of detail involved this is particularly likely to be the case where an expert-devised standard is used to provide a building for a non-expert client. An alternative approach which could help align the building's performance with the client's expectations may be to allow the client themselves to have some input into the definition of the low/zero-energy/carbon building standard with which their building should comply. This will not only allow them a sense of ownership over the building standard, but will also encourage them to understand how the building is designed to work in order to comply with the standard.

This paper examines how a team faced with the challenge of building a zero-energy/carbon building might proceed in a logical way. It starts with a discussion about the various low and zero-energy/carbon standards currently promoted across the world, and uses this to highlight the complexity any client might face when trying to commission a low or zero-energy/carbon building. It then presents a new way of developing such a standard and the approach is applied to the construction of a building. Finally results from a year's monitoring of the building are presented.

3.4. A brief review of low and zero-energy standards

The world of low/zero energy/carbon standards is a confusing and complex one full of surprises and pitfalls through which a design team or client must navigate. Often key terms lack transparency, or the methodology can lead to unforeseen consequences when applied within a design environment. For example, the European Energy Performance of Buildings Directive (EPBD) requires that any new building built after 2020 should be 'nearly zero-energy'. This is defined as a building that has a 'very high' energy performance, and where the 'nearly zero' or 'very low' amount of energy required should be covered to 'a very significant extent' by energy from renewable sources which may be on-site or 'nearby' (European Parliament, Council of the European Union, 2010). To facilitate transition to nearly zero-energy buildings, during the period leading up to 2021, the EPBD specifies the identification by Member States of a cost optimal level of building performance for use as national benchmarks. The methodology used to calculate this level, for different categories of building, is based on the economic lifecycle trade-off between energy-related investment costs (including maintenance and operation) and the resultant energy savings and earnings from renewable energy production. In order to demonstrate either achievement of nearly zero-energy status, or compliance with cost optimal performance levels, it will be necessary to be able to predict and possibly measure the energy performance of the building as well as any relevant renewable energy generation. However, finding a transparent means to do this is far from straightforward. Indeed, the method with which a building is assessed has major implications for the form of building that is delivered. For example, in the UK where CO_2 emission is the metric, a building that uses electric heating and is connected to the grid will look like it performs less well than a building which has the same heating load but relies on gas. This is because, in the UK, the requirement is that electricity use is converted to carbon using the standard UK emission factor of 0.519 $kgCO_2$ per kWh even if the building is equipped with enough PV to meet its annual demand. By comparison, the emission factor for mains gas is 0.216 $kgCO_2$ per kWh (Department of Energy and Climate Change, 2012). Rather than the final metric describing the efficiency with which a building uses energy, the differentiation between the buildings is based to a large extent on the existence of the grid connection.

In addition, with the intended decarbonisation of the electricity grid in the UK (Department of Energy and Climate Change, 2009), the relative performance of these two buildings, as calculated in future, will change dramatically. This begs the question, should today's emission factor, or predictions of that of the future, be used when calculating whole-life carbon emissions?

The use of CO_2 emissions factors is only one example where the methodology lying behind a zero-carbon/energy standard has a substantial impact on the final building. Equally important are questions such as: How to define the energy demand and calculate it? What energy balance period is seen as appropriate? How to calculate offsets in the energy balance calculation? Whether embodied energy is to be considered or not?

3.5. Defining energy demand

As part of a report for the European Commission (Hermelink, et al., 2013), a review of international literature on the subject identifies 75 different definitions for nearly zero-energy buildings, and demonstrates the lack of consistency with which these definitions approach calculating the total energy demand (see Figure 13). While the charging of electric vehicles is not currently common practice and may be reasonably ignored in the general assessment of a building's energy consumption, embodied energy for example does play a significant role (Ibn-Mohammed, et al., 2013) and overlooking its contribution may be less easily justified.

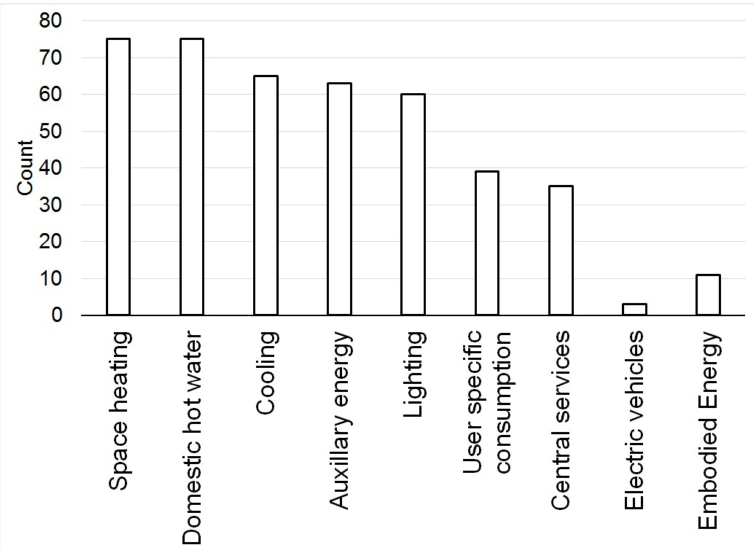


Figure 13: The number of nearly zero-energy building calculation methodologies that include certain forms of energy demand. Data from Hermelink, et al. (2013).

Complexity is further introduced because the energy demand of a building may be measured in terms of the energy delivered to the site, or the primary energy consumed to provide the delivered energy. In a separate review of different zero-energy calculation methodologies Marszal et al. (2011) provide an interesting discussion of the merits of different energy measurement approaches. Although primary energy measurements will, like carbon emissions, be subject to the changing characteristics of a country's energy infrastructure, Marszal (2011) shows that primary energy, which more closely reflects the true environmental cost of energy consumption, is the most used metric in the calculation methodologies covered. However, a look at a number of European low-energy (as opposed to zero-energy) building standards shows less clear preference for the measurement of primary over delivered energy (see Table 10). This is perhaps because, as Marszal (2011) notes, delivered energy is much more easily understood and measured, and the building owner or occupier will receive a bill in units of delivered energy. There are however a number of consistencies apparent in Table 10: Most standards focus on the building's energy in use (estimated by calculation), ignoring the issues of CO_2 emissions and embodied energy (EE), and most calculate the building's energy balance on an annual basis. Some, for example the Living Building Challenge standard (International Living Future Institute, 2014), use a year of measured energy consumption, and Voss and Musall (2013) suggest that the definition of a Net Zero Energy Building (Net ZEB) should be based on a monthly measured balance of energy generation and consumption.

Table 10: Metrics used in the definition of a sub-set of European low-energy building standards. Based on material in Dequaire (2012) and Voss and Musall (2013).

Standard	Description	Energy Type Considered		Other Criteria		Balance period
		Primary	Delivered	CO_2	EE	
Passivhaus	Internationally recognised low energy building standard	Total <120kWh/m^{2}a	Heat <15kWh/m^{2}a	No	No	Year
Norwegian proposal for a passive house	Inspired by the Passivhaus standard		Heat <15kWh/m^{2}a	No	No	Year
Swedish passive house standard	Inspired by the Passivhaus standard		Total <34 - 60kWh/m^{2}a	No	No	Year
Swiss Minergie-P	Extension of the Swiss Minergie low energy building standard		Total <30kWh/m^{2}a	No	No	Year
Danish Lavenergiklasse 1 (low energy class)	Best energy class for buildings in the Danish code		Total kWh/m^{2}a	No	No	Year
French BBC-effinergie® label	French low energy building standard	Total kWh/m^{2}a		No	No	Year
UK Zero-carbon	British low energy building standard		Total kWh/a	Primary kgCO_2/a	No	Year
Net ZEB	Zero energy building concept	Total kWh/m^{2}a		No	No	Month

3.6. The energy balance period

The design of a building may allow it to produce energy equivalent to, or even exceeding, its demand. However, it is usually the case that demand and production do not match all the time, and the building will import or export energy at certain times of the day or year. A Net Zero Energy Building (Net ZEB) is defined as "an energy-efficient building that, within its annual balance sum, covers its entire annual primary energy demand in connection to the electrical grid and further grids if required, based on a monthly balance via primary energy credits for surplus energy feed-in" (Voss & Musall, 2013). In this case it is the balance of energy demand against energy production that is important. It is not enough for the building to produce as much energy as it uses over the course of a year, but it is when the energy is produced and used (known as the 'load-match') that is scrutinised. The monthly load matching factor (f) is calculated by dividing the energy generated by the energy that is consumed in each month, as in Equation 1:

Equation 1

$$f = min\left[1, \frac{generation}{consumption}\right] \times 100\%$$

The twelve monthly factors are then averaged over the year. Under the Net ZEB rules the load match factor can never be greater than one (100%), and any surplus energy is considered separately (Voss & Musall, 2013). The aim is to encourage the design of buildings and renewable energy technologies where energy demand and production correspond temporally, at least when measured on a monthly cycle. This is in contrast to the situation where a large amount of energy is exported to the grid at a time when the building doesn't require much energy and production is high (for example from roof-mounted PV in summer) which is offset by an equal amount of energy drawn from the grid at a different time (for example in winter). Assessing the load-match on a monthly basis is advocated as it allows the demand on grid storage, with its consequent CO_2 emissions usually hidden in annual demand/generation calculations, to be better appreciated. This mechanism still does not determine with any accuracy the true level of demand from the grid, as total monthly generation and consumption are being compared, but it helps to demonstrate the seasonal variation in dependency of the building on the grid. Where demand can be better covered by self-generation when and where required, grid effects will be less significant than where the grid is effectively used as a storage facility. This is because any excess energy 'stored' in the grid and 'retrieved' when needed incurs the normal environmental costs such as transmission losses and primary energy factors. Unless a building is truly self-sufficient it will always rely on being able to draw some energy from the grid at times when demand for energy exceeds the renewable energy supply.

The importance of the temporal relationship between energy demand and supply has been identified (Ampatzi & Knight, 2012). A finer load-match resolution, for example on a daily, hourly or even minute-by-minute basis, would provide an even more accurate representation of the building's reliance on grid storage. However, the challenge of estimating the energy demand to such levels of detail would be significant. As mentioned above, the Living Building Challenge standard (International Living Future Institute, 2014) overcomes this problem by using measured energy consumption data in its determination of compliance.

3.7. Offsetting demand in the energy balance

As well as identifying what should be included in the calculation of the energy demand of a building, it is also necessary to determine how this energy can be offset in calculations. This computational adjustment is necessary as most buildings are connected to some form of energy grid and are rarely entirely self-sufficient. The simple way, and the way most frequently used in the various standards, is to balance the annual energy demand of a building against its annual renewable energy production. However, aside from the balance period complication addressed in Section 3.6, this raises the question of what should count as new and relevant renewable energy production. Energy produced by a technology attached to the building, can clearly be attributed to the building, but it may be the case that the energy for offsetting is produced by a local renewable energy infrastructure that the building is connected to. There is also the need to consider what is meant by local. For example, is a PV panel sited on a bike shed adjacent to the building truly part of the building, and is a wind turbine on a University campus any different than one several hundreds of miles away if both are owned by the same University? Torcellini et al. (2006) describe four different ways this is tackled in Zero Energy Building (ZEB) standards: site energy balance; source (primary) energy balance; energy cost balance; and related energy emissions balance. These different definitions lead to the design of different buildings. The range stretches from 'aggressive energy efficiency' for a *site energy ZEB*, to the need for no energy demand savings for an *off-site ZEB* where the goal can be reached by simply purchasing off-site renewable energy. A similar approach is taken in the UK definition of a zero-carbon building, where some of the carbon cost of the building can be offset with 'allowable solutions' which may include investment in offsite renewable energy infrastructure, or payment of a carbon fee (Pelsmakers, 2012). Here the building doesn't even necessarily need to be receiving the additional renewable energy to be classed as zero carbon.

3.8. Global development of zero-energy standards

The developed world, particularly the EU and the US, already has well established energy policies (GLOBE International, 2013; Pan & Ning, 2015) that have filtered down into building energy standards. National energy policies, such as building standards, play an important role in the control of energy consumption, and where strong policies are absent growth in energy consumption and carbon emissions is evident (Nejat, et al., 2015). Developing countries tend not to have comprehensive building energy policies, but there is evidence that climate change related legislation in many such countries is growing rapidly (GLOBE International, 2013). For example, China, India and South Korea are all actively pursuing pilot schemes or legislation focussed on pricing and trading carbon emissions. In the case of South Korea the government has set a target of 2025 by which time all new buildings will be zero-energy (Nejat, et al., 2015).

While building energy policies contribute to reduced energy consumption, many argue that these need to work in conjunction with end-user engagement in order to be as effective as anticipated (Pan & Ning, 2015). In addition to consideration of the thermal envelope and passive heating and cooling strategies, human factors were also accounted for in the design of a net zero energy building in China (Jin, et al., 2014). Facilities for composting and greywater treatment were incorporated to encourage the occupants to engage in environmentally conscious behaviour and reduce energy consumption and carbon emissions. As zero-energy/carbon building standards develop more emphasis may need to be placed on factors such as occupant behaviour and wider government policies aimed at the evolution of energy infrastructure.

3.9. A new way of creating a zero-energy standard

Given the plethora of possible standards and proto-standards, a design team has great flexibility in choosing a low-energy standard, but because of the inherent complexities summarised above, there is also the possibility that they will be left swimming in a sea of confusion. Additionally, there may be the need to consider the client's perspective about what is meant by a low- or zero-energy building. Most standards are in terms of intent, whereas the public think in terms of reality. To the public, a low energy building is one that uses little energy in practice, not one that is designed to use little energy. Such is the scale of the performance gap that the reality is that many buildings designed to low energy standards use no less energy than buildings constructed against normal building codes thirty or more years ago (Dasgupta, et al., 2012; Sunikka-Blank & Galvin, 2012). The Passivhaus (PH) standard has an advantage in this area due to the number of buildings that have been built (>50 000) with a close match between intent and results as shown in numerous field trials, see Figure 14. However, for a client that wishes to create a zero-energy rather than a low-energy building, PH creates a problem in that it does not yet include a way to account for renewable or embodied energy. It is also a design not a performance standard.

The PH standard was excluded from consideration in Hermelink's report (Hermelink, et al., 2013) (discussed in Section 3.5), as it was not deemed to comply with the nearly zero-energy concept. It was, however, acknowledged that heat demand is drastically reduced where the PH strategy is followed (Hermelink, et al., 2013). In contrast to the nearly zero-energy concept, with its focus on the energy demand/generation balance, the PH building standard concentrates on energy efficiency and sets specific maximum energy demand targets. The two PH energy limits (15kWh/m^{2}a heat demand, 120kWh/m^{2}a total primary energy demand) are deliberately set to encourage the design of buildings that use energy efficiently (Cotterell & Dadeby, 2012), rather than buildings that can produce lots of energy. In response to the EPBD's requirement for renewable energy generation, the Passive House Institute recently discussed two additional categories in the PH standard (Passive House Institute, 2014). The definition of these new PH levels is based on the amount of energy generated in relation to the building's footprint (e.g. kWh/m$^2_{ground}$a).

Given the issues and complexity identified, one logical way for a design team to select a zero-energy/carbon standard might be to simply ask the clients what their view of the term zero-energy is. For example: Is it an environmentally-driven design intent? Or do they expect to simply never receive a utility bill? Are they interested in including embodied energy? Do they consider emissions related to the transport of those using the building over its lifetime to be relevant? Ultimately the use of standards that lead to the construction of buildings that genuinely reflect the views of clients and occupants is likely to help in ensuring the zero-energy concept gains traction and leads to mass construction of such buildings. This fits in well with the findings in Kershaw and Simm (2014) where they state that: “It is suggested that most barriers [to low energy design] could be overcome by improving communication between the design team, client and end users”.

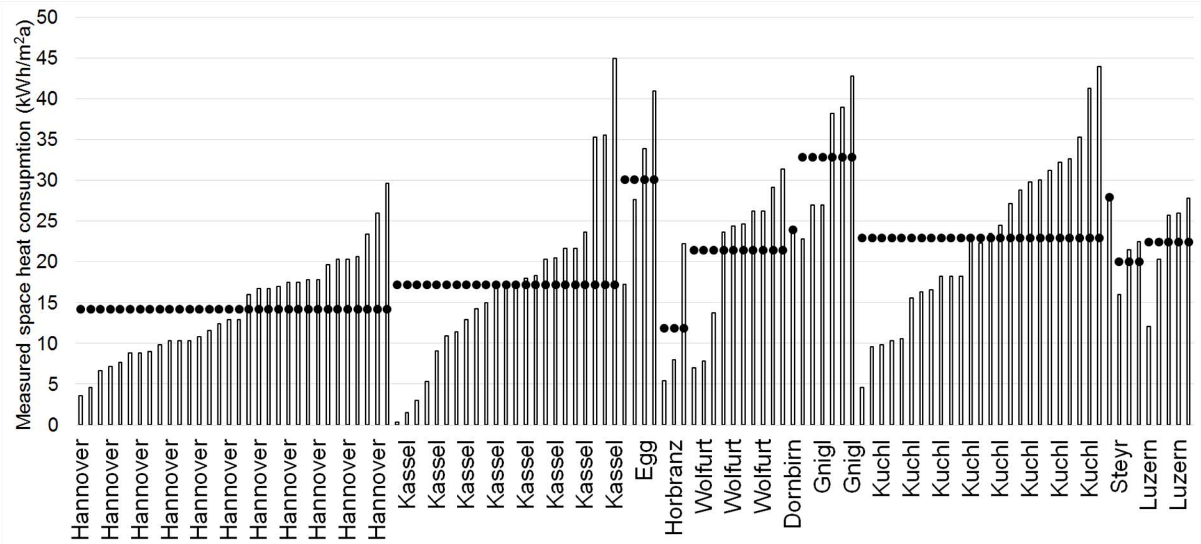


Figure 14: Measured space heating consumption of various Passivhaus buildings in a series of locations. Dotted lines indicate mean consumption for each location. Data from CEPHEUS (Feist, et al., 2001).

3.10. Method

To discover if the creation of a client-led zero energy standard was possible, practical and might ultimately lead to a successful building, a client group was identified that was about to commission a low/zero energy/carbon building. The proposed building was a 450 pupil school. The client group where defined as the head teacher, 16 members of teaching staff, three members of non-teaching staff, five parents and six representatives of the local authority (who were paying for the construction of the building). The architect, engineers and the construction company used on the project were not considered part of the client group. As the client group were non-expert in the field of zero-energy buildings they were given a lecture (approximately 30 minutes) on climate change and UK energy policy, and a lecture (also approximately 30 minutes) on zero and low energy building standards from around the world with terms such as embodied energy and emission factor being explained. The purpose of the lectures was to inform the group about the concepts and language surrounding energy, CO_2 emissions and building standards, and the different methods that can be used to achieve a zero-energy building. It is possible that the lectures may have influenced the client group’s view on the overall value of zero-energy buildings, however it was necessary to provide them with relevant information in order that they could meaningfully consider what a zero-energy building meant to them. They were then asked to anonymously complete a questionnaire designed to determine what they thought should and should not be used as criteria for the zero-energy/carbon standard used for the new building. Nineteen possible endings to the statement “the criteria for the definition of a zero-carbon building should…” were presented along with a scale allowing the respondent to indicate how strongly they agreed with the criteria. The five-point scale ranged from minus 2 (strongly disagree) to plus 2 (strongly agree) with 0 expressing neutrality. The final question asked the respondent to indicate what they thought was an appropriate balance period. In order to maintain the anonymity of the respondents the completed questionnaires were analysed collectively without identifying individuals and their particular responses. Figure 15 and Figure 16 show the results. All members of the client group completed all the questions.

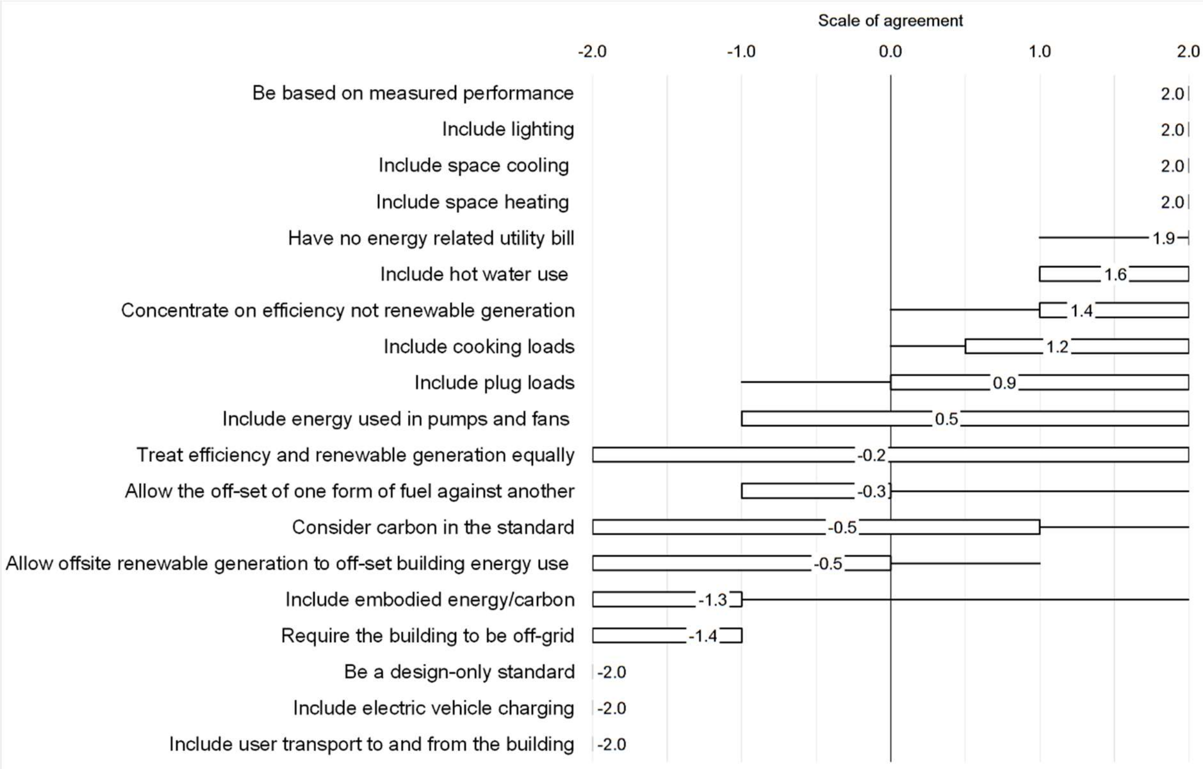


Figure 15: Client agreement with zero-energy criteria. Mean response values shown. Interquartile range indicated by box lengths. Where outside the interquartile range, the maximum and minimum response values are indicated by horizontal line lengths.

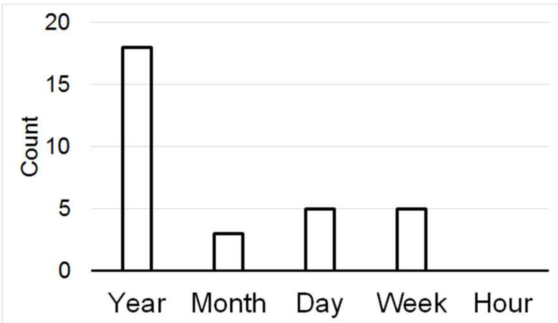


Figure 16: The number of client responses for the question about different potential balance periods.

Given the results shown in Figure 15, the key lessons learnt from this exercise were that, for this client group, a zero-energy/carbon standard: is a performance not a design standard; should lead to no energy bills; and should be based on efficiency not generation. It was evident that issues like embodied energy and transport were much less important to the client group.

After analysis of the survey results, the following definition of a zero-energy/carbon standard was presented to the client-group:

> *The building will be zero-energy in-use as defined by having no energy utility bill, and this will be a performance not a design standard.*

Using the same feedback process with other client groups and sites might produce different results.

3.11. Implications

The standard created by the client group is a very simple succinct standard, especially when compared to the standards discussed above, but it left many questions about delivery unanswered. Most worrying for the design team and the builder was that it is a performance not a design standard, and, because it is related to the utility bill, left little room to manoeuver if the standard was found to not to have been met once the building was constructed.

The Passivhaus concept was chosen for the basic design philosophy because of the success that Passivhaus has had in matching intent to reality (Figure 14). The standard takes an holistic approach to both the design and the construction process, and makes very specific demands such as: compulsory qualification of designers (Certified Passive House Designer/Consultant Examination); use of a single software environment (PHPP) that has been proven against post construction data; minimising the size of heat systems so poor occupant behaviour is less likely to lead to excessive energy use; policing of the design and build (in country); and policing of the policers (back in Germany). Adopting Passivhaus can be viewed as a way of minimising risk if the client's expectation is for a zero-energy building with compliance judged from measured energy consumption.

After deciding upon Passivhaus as the heating/cooling energy standard, it was necessary to choose a method for the inclusion of renewables into the calculation. The survey results indicated that the clients seemed to appreciate the rationale of offsetting imports and exports of the same fuel over the property boundary when balanced over a time period that is common and visceral. The survey showed a preference for balancing over a year, see Figure 16, so the design team chose a 365 day cycle for balancing. In addition, it would be easier to meet the zero-carbon target when balancing over this period (data is presented later to show this). The implication of this was that a utility cost might result over the winter period, but this would be offset by a negative bill over the summer.

Based on the survey results, it was decided that the building could not be connected to the gas main. This was because gas flows cannot be directly offset on a like-for-like basis, unless a building is fitted with the technology to produce hydrogen or methane for injection into the gas main. This was not to be the case here, and in essence meant the creation of an all-electric building, or the use of biomass. Given the intent to use the Passivhaus standard for the project, the space heating load would be very low and the design would not include radiators or underfloor heating. In addition, in order to comply with the Passivhaus requirement for primary energy (demand limit of 120kWh/m^{2}a), solar thermal would be used for much of the domestic hot water (DHW) demand. This and the very low space heat demand led the engineers to consider that biomass would not be economic.

This left the choice between PV and wind for the generation of power. Small-scale wind has a poor record in the urban environment (the site is situated in the middle of a town) with generation often being far lower than suggested at design stage (Peacock, et al., 2008). Hence many see it as a risky strategy at such locations. PV on the other hand has the opposite reputation, with annual generation often being equal to or exceeding that suggested at design (Eltawil & Zhao, 2010; Li, et al., 2013). To match with the client group's view of not offsetting across the boundary of the building it was deemed likely that they would only see the building as zero-energy if the PV was mounted on the building. This conclusion had a strong influence on the shape of the building (see Section 3.12.2).

In summary, in order to produce a cost effective building, with an acceptable level of risk, that matched with the environmental standard this particular client group created, and would therefore be accepted by them as zero-energy/carbon, there was a logic in choosing to build an all-electric Passivhaus with roof-mounted PV generation, where the annual cycle is used for balancing demand against production, and which ignores the questions of embodied energy and transport etc. It is perhaps not surprising that a client should want their zero-energy building to incur no energy bill. However, most zero-energy building standards focus on design, rather than performance, and there is often a gap between design intent and reality. There is therefore potential for the current top-down government- or industry-imposed definitions of the term "zero energy" to have limited meaning in practice from the client's perspective, despite a building's compliance with the zero energy definition used. The client-led approach to defining the building standard described here means that compliance must be demonstrable through performance in a way that is clearly understandable by the client.

3.12. Application

In a design environment where teams are used to only meeting unambitious national building codes and where the energy aspects of these are only design standards, not in-use requirements, the need to design a building that would survive the pressures and vagaries of the construction process, be within budget and whose success would be measured in terms of the first year's energy bills was a considerable risk. This led to the selection of products and methods for the construction that had been applied before by the team, were not novel and where the measured performance was most likely to closely match prediction.

3.12.1. Fabric and heat demand solutions

The chosen solution was the off-site construction of insulated concrete panels. This was potentially unfortunate as it ensured the embodied energy and embodied carbon of the school would be high, but this was felt justified if the approach meant it would be easier to meet the zero-energy in-use target, and because embodied energy had not been considered an issue by the clients.

With the building designed to Passivhaus standards, it was felt that the very small amount of heat required did not justify a separate heating system or the use of hot water based heater batteries, so simple electric heating elements were placed in the air supply ducts to each classroom.

There is a natural synergy between heat gains provided by school pupils, Passivhaus design and thermal mass. The heat output of a person is around 100W (Szokolay, 2008), and a high mass approach that maximises the retention of the pulse of heat provided by the pupils has merit; especially if this pulse is greater than the typical overnight winter losses. In a typical school occupancy density can be very high in some areas (>0.6 people per m^2), but very low in other areas when averaged over the school day. The difference in occupancy densities between spaces suggests that the natural approach would be to supply fresh air to each classroom and let this air flow through corridors and rooms with low occupancy, thereby heating these low occupancy density areas. This is only likely to be successful if the thermal mass is high, allowing the moderation of internal temperatures, and a mechanical ventilation with heat recovery (MVHR) unit is included in the ventilation system.

There is an extensive literature on problems with building management systems (BMS) causing buildings to be run in an incorrect and possibly in inefficient way, often due to poor commissioning or maintenance of the BMS (Li, et al., 2013). In schools this has led to the heating system operating when windows have been left open or during the holiday periods. Hence it was decided to control the duct heaters via a simple teacher-operated switch in each classroom that gives 15 minutes of heat. The design team were aware that electrically driven windows under BMS control also had a reputation for being expensive and poorly controlled, so manually opening windows were used for the majority of the building. The idea being that given the heating system could not make up for the losses from inappropriate use (because of the 10W/m^2 Passivhaus limit), staff would not leave them open in winter unnecessarily, or overnight, as they would be cold the next day if they did. This matched well with the presence of the MVHR system, as it allowed the school to ensure that classrooms would have good air quality with the windows closed, and hence could simply inform the staff which months they should keep the windows closed.

3.12.2. Primary energy consumption and renewable energy generation

The PH standard places an overall limit on the total primary energy consumption (120kWh/m^2a). One potential problem with the school that was known from conception was its location in a neighbourhood of low average income. This meant the proportion of pupils having free school meals would be high, meaning the kitchens would have a higher than typical energy requirement. In addition, given the growing use of IT in schools, it was clear that electricity use needed to be minimised aggressively.

Kitchen energy demand was reduced in three ways: induction hobs, solar hot water and a DHW heat pump. The induction hobs and heat pump arising as a natural implication of the building being all-electric. One, non-energy, benefit of the induction hobs being that even young pupils could safely use the kitchen for cookery lessons. IT energy use was reduced in two ways: replacing all PCs with laptops and the use of charging trollies. At the end of each day, all the laptops are plugged into these trollies and wheeled into secure cupboards. The cupboards are then supplied with electricity for 2 hours. This means computers cannot be left on charge over holiday periods, and are secure against theft.

The need to find a cost effective solution which had enough space on its roof for the amount of PV needed to support the various activities of a school suggested the basic form and orientation of the building, this choice was aided by the requirement of Passivhaus of a low ratio of surface to floor area. The resulting design was a single building (rather than a series of detached blocks), rectangular in plan, and wedge shaped, with the slope (roof) of the wedge facing south and covered in PV (see Figure 17, Figure 18 and Figure 19). This left the main, double storey, facade of the building facing North, and a single storey facing South. This is an ideal situation for a school, as the classroom accommodation needed is of approximately twice the floor area of the sum of the areas needed by other forms of accommodation, and ideally needs to face North to ensure solar gains are not an issue in densely occupied spaces and that the sun cannot make the use of white boards difficult. A side effect of the wedge shape was that it left a large attic space ideal for housing the large MVHR units, PV inverters, solar hot water storage vessels and air source heat pump. The heat pump is used to provide DHW when the solar hot water system cannot meet the load.

The 120 kWh/m^2 Passivhaus annual limit on primary energy, together with the need for all generation to fit on the available roof area, were found to be surprisingly well matched. The result was a 2 786 m^2 school for 450 pupils which opened in October 2011.

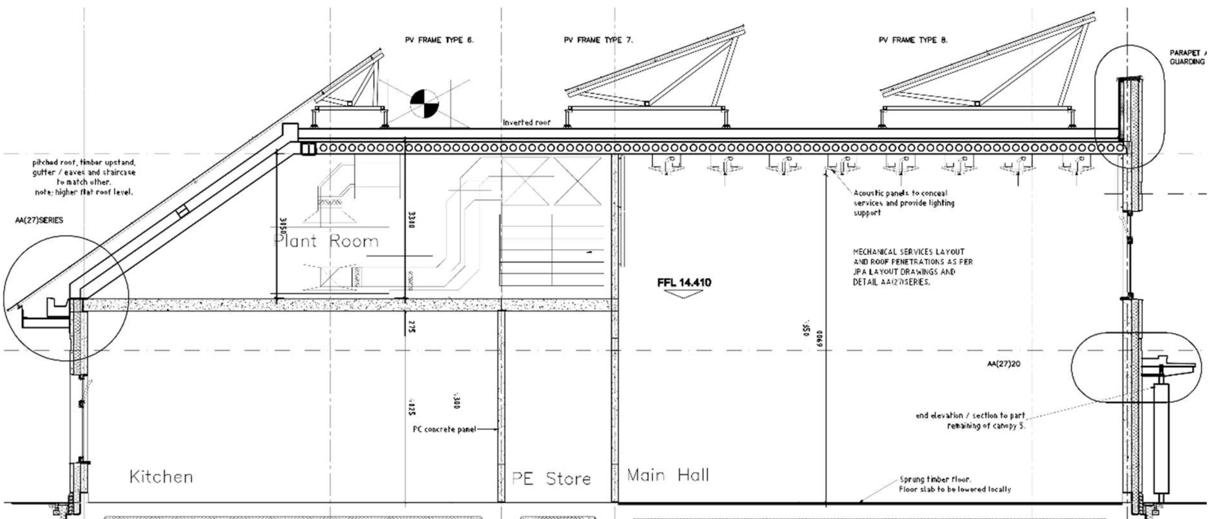


Figure 17: Section of the school.

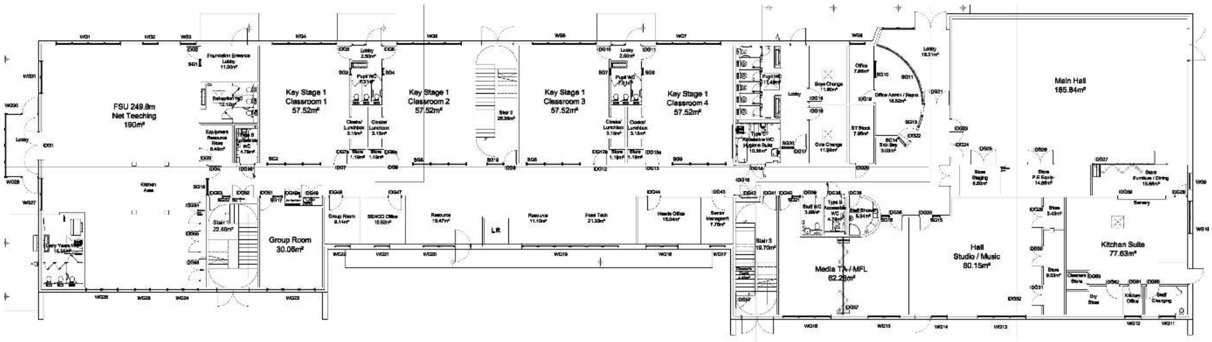


Figure 18: Ground floor plan of the school.

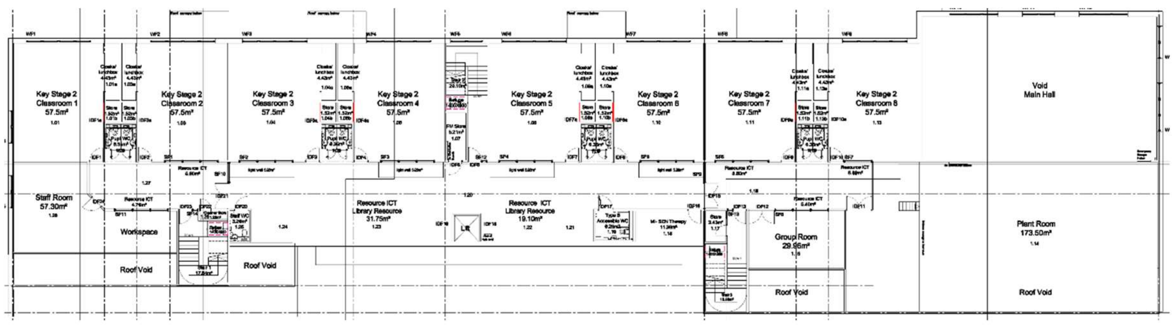


Figure 19: First floor plan of the school.

3.13. Monitoring results

The building is being monitored using both the data from the BMS, the main utility meters and a variety of other sensors. Of particular interest here is the data relating to energy use and PV electricity generation, although data on various other environmental performance indicators, such as carbon dioxide levels, internal temperatures and acoustics were also assessed. The main reason for the monitoring is to provide evidence to the client group that their definition had been met without other environmental expectations being compromised. For example, while the Passivhaus standard aims to reduce heat demand, the requirement for an air-tight building envelope to minimise heat loss through infiltration has the potential to result in poor internal air quality if the MVHR unit is not used successfully by the occupants. Also, the use of an MVHR system which uses the corridors as the return air path necessitates the free flow of air within the building which could present acoustic problems.

3.13.1. Electricity

Half-hourly readings from the inverter control panels were used to determine the amount of electricity generated by the PV panels. Over the course of a school day it can be seen that there are periods when electricity is imported from the grid (in particular overnight), and periods when the PV production is such that little or no import is needed (see Figure 20). PV production and the consequent electricity import required varies with the available levels of sunlight. The monthly profiles show, as expected, a decline in output during the autumn and a rise in spring (see Figure 21), with the ratio between maximum and minimum monthly generation being approximately 4. This suggests that if a strict monthly balance had been demanded as part of the zero-energy standard, a 554kW$_{peak}$ array would have been required (instead of the 168kW$_{peak}$ one fitted). Aside from the fact that this would have added greatly to the cost of the building, there is not sufficient roof space to accommodate such an array.

This observation clearly indicates that care will be need if a zero-carbon standard is defined in terms of a measured monthly balance of import and export. This is because the variation in generation between the same month in different years is far greater than the difference in total annual production between years. For the UK variation in hours of sunshine for a month compared to the long-term average for that month can be in excess of 40%, whereas the annual variation is likely to around 5%. This could easily lead to the building failing to meet a measured monthly energy balance.

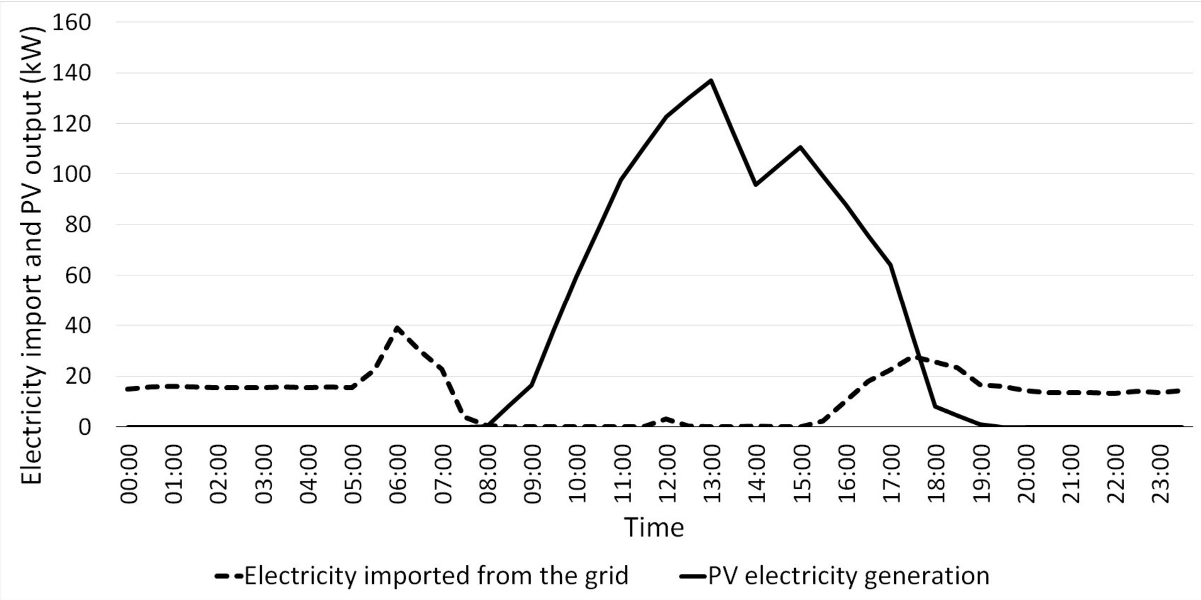


Figure 20: Measured electricity import and PV production over a sunny Tuesday in October.

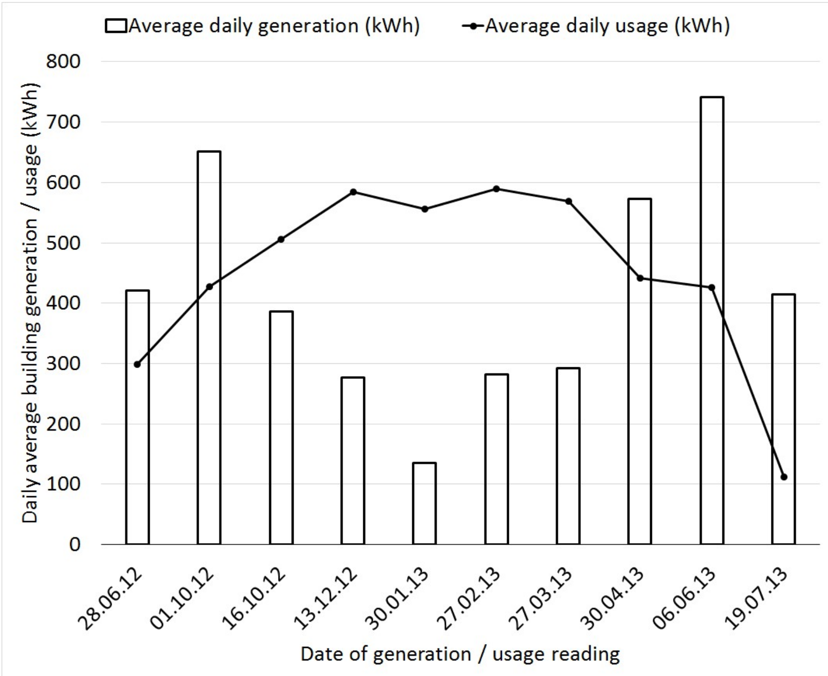


Figure 21: Consecutive measurements of electricity generation and usage during the period 15.04.12 to 19.07.13 normalised to reflect the number of days between readings.

Measurements running from 23rd September 2013 to 8th September 2014, show a net export of 20 870 kWh (13.1% of the school energy demand during this period). Energy consumption during this period was 159 199 kWh. This is 59 kWh/m^{2}a (assuming a floor area of 2 786 m^2).

Applying a primary energy factor of 2.6 (as is used in PHPP) and factoring up for the monitoring period being slightly less than a year gives 153.4 kWh/m^{2}a. Applying the UK primary energy factor of 3.07 (Department of Energy and Climate Change, 2012) results in a value much greater than the Passivhaus primary energy design limit. However, as Figure 22 shows, the school's energy demand is much lower than UK good practice for primary schools (Department for Education and Skills, 2007), and falls within the lowest 10% of consumption for primary schools in England and Wales (CIBSE, 2012).

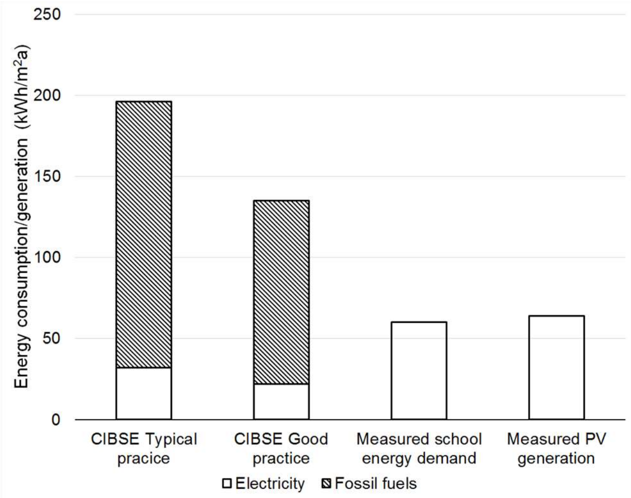


Figure 22: Measured school energy demand compared with CIBSE Typical and Good Practice benchmarks (Department for Education and Skills, 2007). Measured school PV generation also shown.

3.13.2. Internal temperatures

Temperature dataloggers were placed in the locations shown in Table 11 to monitor both occupied and unoccupied periods.

No internal temperatures exceeded 28°C during occupied periods, indicating that overheating appears to not be a problem, and average temperatures are comfortable. Minimum temperatures whilst cool are above 15°C.

Table 11: Temperature statistics from dataloggers.

	All Data			Occupied Periods			
Room	**Min, °C**	**Ave, °C**	**Max, °C**	**Min, °C**	**Ave, °C**	**Max, °C**	**Hours > 28°C**
Main Hall	15.6	20.9	25.7	15.6	20.8	25.7	0
Classroom 1	17.2	19.0	21.7	17.7	19.8	21.7	0
Classroom 8	16.6	21.1	25.6	16.6	21.2	25.6	0
Classroom 10	16.1	20.8	25.1	17.1	20.9	25.1	0
First Floor Resources	17.2	21.9	26.7	17.2	21.6	26.2	0
FSU	16.5	18.3	21.0	17.0	19.3	21.0	0
Entrance Outer Lobby	11.6	20.6	25.6	13.1	20.2	25.6	0
Entrance Reception	17.1	21.2	28.6	17.1	21.0	24.6	0
External	-1.9	9.2	32.6	-0.9	10.8	27.1	0

3.13.3. Internal carbon dioxide concentrations and acoustics

CO_2 concentrations are indicative of the adequacy of ventilation. Building Bulletin 101 (Department for Education and Skills, 2006) recommends that ventilation provision in teaching and learning spaces should be sufficient to ensure that the average CO_2 concentration at seated head height should not exceed 1 500 ppm averaged across the school day, and that the maximum CO_2 concentration should not exceed 5 000 ppm.

The average CO_2 concentration was calculated from the half-hourly readings for each school day (between 09:00 and 15:30), and was determined to be 938 ppm. The occupied

CO_2 concentration never rose above 5 000 ppm, and only two days during the first year of operation had an occupied average exceeding 1 500 ppm. Figure 23 shows an example of a daily profile of indoor CO_2 concentration levels.

The acoustics of the school in terms of reverberation, ingress, room-to-room transmittance and background noise from services were all found to be compliant against national standards, as given in Building Bulletin 93 (Department for Education and Skills, 2003).

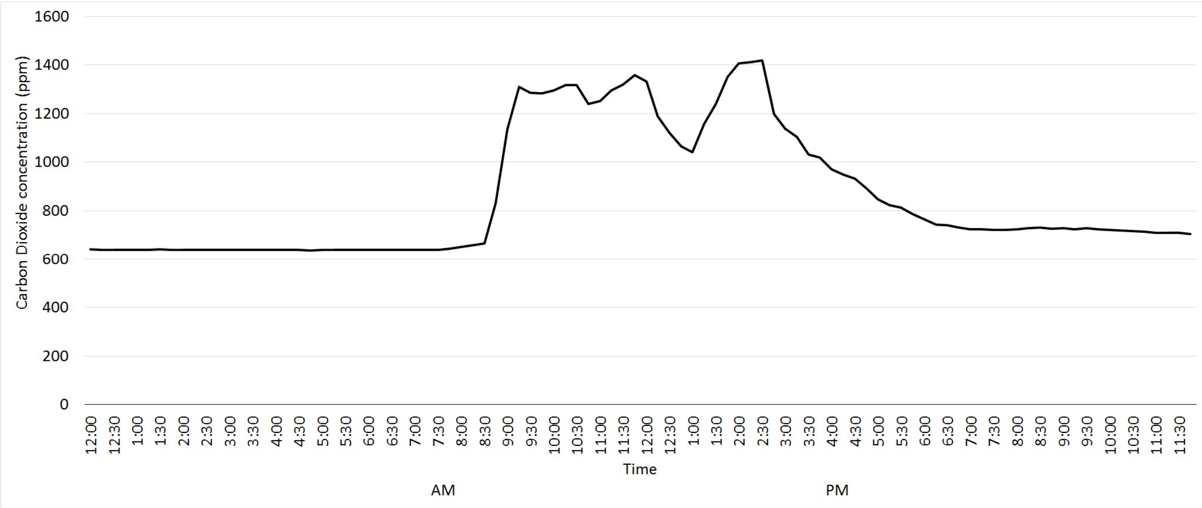


Figure 23: Measured indoor CO_2 concentration levels in a classroom over a Monday in January.

3.14. Conclusion

This is the first time that a client-based method for defining an energy standard has been derived from a systematic survey and implemented in a building project. The work demonstrates that a client group is capable of engaging with the zero-energy concept and contributing towards relevant design criteria. It is also evident that such criteria can successfully be incorporated into a building that fulfils both the needs of the building users and the demands of the client-based zero-energy standard.

A survey of the client group's view of zero-energy crystalized into a standard that required the school building to be zero-energy in use, i.e. incurring no annual energy utility bill. This had deep implications for the overall design of the building, as it was necessary to accommodate enough PV on the roof for the generation of sufficient electricity to offset annual consumption. The resulting shape and layout of the school worked well to satisfy the needs of the building users, and also provided a natural space to accommodate the MVHR, and other, services required in the design.

The Passivhaus design philosophy followed has resulted in a building that maintains an acceptable internal environment, from the perspective of temperature, CO_2 levels and acoustics, while keeping the primary energy demand very low at approximately 153.4 kWh/m^{2}a and the heating energy use to almost zero. This is even despite the fact that the school has to provide an above average number of hot meals. With a PV array capable of generating more energy than the annual demand, the building has been successful in meeting the design criteria, in particular the client group's view of what a zero-energy building is.

3.15. Acknowledgements

The authors are grateful for the helpful assistance given by Chris Rea of NPS South West Ltd in the preparation of this paper. This research was partly funded by the Engineering and Physical Sciences Research Council (grant number: EP/L016869/1).

3.16. Postscript

This Chapter has shown that it is possible to design and construct a building that successfully complies with an easily understandable client-defined zero-energy standard. The work in this Chapter has also demonstrated that the requirements of zero-energy building standards can vary depending on the perspective of the specifier, but that some consistency in approach is evident. For example, almost all zero-energy building standards balance energy demand and renewable energy generation on an annual basis.

However, even if the balance period is agreed the definition of the energy balance also has design implications. For example, if the PHI's PER concept is applied to this net zero-energy school, a different assessment of the building's performance would result (see Table 12). A larger PV array would therefore be needed in order to make up for the losses associated with the storage and retrieval of renewable energy generated on site.

Table 12: Measured electricity demand and PV generation for the 2,786 m^2 net zero-energy school in Exeter over the period 13/10/2011 – 08/09/2014. Data source: Mitchell (2014).

Energy application	PHI PER factor	Measured (site) value (kWh/m^2a)	PER value (kWh/m^2a)
Electricity demand	1.4	64	90
PV generation	1	66	66
Net demand (demand – generation)		-2	24

An alternative approach was taken to the design and construction of a new science department for a school in Bath, in southern England. In this case, the client's brief was that the new building would demonstrate sustainable building structures to the students. The response to the brief was to focus on embodied carbon – the carbon dioxide, or greenhouse gas emissions, tied up in the fabric of a building as a result of manufacturing processes – rather than operational energy. The result is a solid-timber construction insulated entirely with straw (Pelly & Mander, 2014), which includes no renewable energy generation technology. Instead of relying on energy generated on site to offset energy demand, the carbon sequestration properties of the straw and wood – the carbon dioxide captured in organic materials in the growing process – are used to offset the carbon emissions that arise as a result of energy demand. It is estimated that enough carbon is sequestered in the fabric of the school building to offset seven years' worth of carbon emissions arising from its operational energy demands (see Table 13).

Table 13: Embodied and operational carbon emissions associated with low embodied carbon school building. Data source: Pelly & Mander (2014).

Embodied and operational carbon in Hayesfield School science department building	
Embodied carbon	-126 $kgCO_2e/m^2$
Operational carbon	17.5 $kgCO_2e/m^2a$
Number of years offset	7

The designers of the school building also considered what the embodied carbon impact would have been had a more traditional scheme using concrete or steel been used (see Table 14). This included the scenario in which carbon sequestration is ignored, reflecting the fact that the use of timber products in particular is not universally viewed as having a net beneficial impact on global carbon emissions. For example, the Inventory of Carbon and Energy (Hammond, et al., 2011) points out that, if timber is being consumed faster than it is grown, it is unrealistic to view the use of timber products as having a net global positive impact on carbon emissions. Equally, in the case of unsustainably sourced timber, deforestation has the effect of actively contributing to carbon emissions (Weight, 2011).

Table 14: Data source: Pelly & Mander (2014).

Embodied carbon of schools in different structural materials	
Scheme	**Embodied carbon $kgCO_2e/m^2$**
Straw with sequestration	-125
Straw without sequestration	161
Concrete	206
Steel	217

Both these school buildings comply with a ZeroCC concept that has shaped their design. The Exeter building can be described as a net zero-energy building, based on PV electricity generation balanced against demand on an annual basis, but in this case embodied carbon is ignored. The Bath building can be described as a net zero-carbon building (at least for the first seven years of its life), based on carbon sequestration in the fabric of the building offset against carbon emissions from operational energy demand, but renewable energy generation is not included in the design. In both cases, a slight change to the net zero rules would mean that the buildings are no longer compliant; a monthly import-export balance for the Exeter building, and discounting carbon sequestration for the Bath building. The similarities and differences between these two building concepts raises a number of questions:

- If the net zero-energy Exeter building is assessed using the same criteria as the net zero-carbon Bath building, and vice versa, would they both still reach the ZeroCC goal?
- From a climate change perspective, is it possible to say if one building performs better than the other?
- How can the design and performance of each building be optimised under the net zero-energy rules, the net zero-carbon rules, or both sets of rules? What is the impact of making slight changes to the rules, as described above?

The design of the two school buildings described in this Chapter were a response to bespoke ZeroCC concepts developed for each construction project individually. However, there are in existence more generic compulsory and voluntary ZeroCC concepts that have been developed to be applicable to particular types of building. The following Chapter looks in detail at three different dwelling-specific ZeroCC concepts that have been applied in the UK. The implications of these different concepts raises further questions about what a ZeroCC building really is.

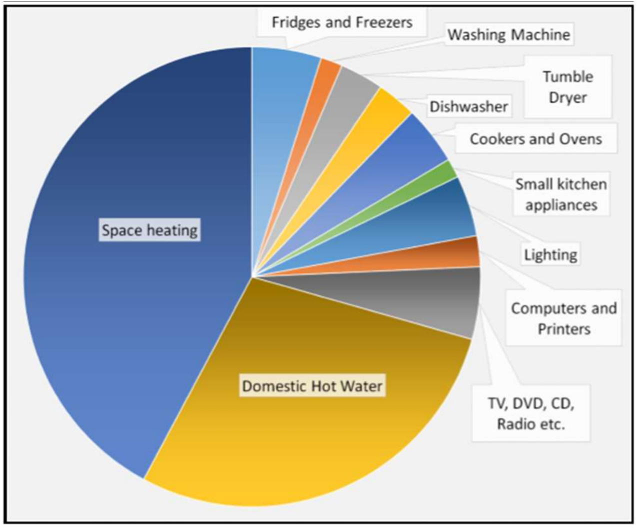
Chapter 4. ZeroCC concepts applied to dwellings in the UK

The UK's Committee on Climate Change (CCC) has estimated that, alongside the required reductions in emissions, up to five million new homes need to be built in the UK by 2030 (and eight million by 2050) to meet current housing needs and accommodate a growing population; amounting to about a fifth of the housing stock (Committee on Climate Change, 2018c). There is a need to ensure that emissions arising from the construction and operation of new homes are minimised as much as possible, so the focus of this chapter is ZeroCC concepts that have been applied to new dwellings in the UK.

This chapter starts with a description of a typical UK dwelling, and then describes three approaches that have been used to address the need for ZeroCC dwellings in the UK. The first ZeroCC concept described is the UK's Zero Carbon Home concept. It was originally envisaged that the requirements of the Zero Carbon Home would be enshrined in law. However, the challenges of compliance perceived by the UK construction industry eventually led to the demise of this concept as a legal requirement. The second ZeroCC concept considered is Passivhaus certification. This is not a legal requirement in the UK, but it is a well-established framework that has been, and continues to be, applied widely throughout Europe and beyond. The last ZeroCC concepted discussed is the UK Passive House. This is an idea for a ZeroCC concept that builds on the original Passivhaus concept, but tailors design requirements to the UK climate. Consideration of the details of these ZeroCC concepts raises further questions which are presented at the end of this Chapter.

4.1. Typical UK dwellings

The UK's Committee on Climate Change describes a typical residential building as a "three bed semi-detached dual fuel household" (Committee on Climate Change, 2017). In the UK gas tends to be used for heating and hot water, while electricity is used to provide energy for everything else. According to the UK's Standard Assessment Procedure (SAP) for domestic buildings, the carbon intensity (CI) of UK gas (the GHGs resulting from each kWh of energy demanded) used in the building assessment is 0.216 kgCO_2e/kWh, while that of electricity is much greater at 0.519 kgCO_2e/kWh (Department of Energy and Climate Change, 2012). The result for the typical UK house is that, although the majority of the energy is used for heating (space and water), the majority of GHGs arise from the demand for electricity (see Figure 24). Overall, when viewed through the eyes of SAP, the annual demand for energy (gas and electricity) in a typical UK house leads to annual emissions of about 3.4 tCO_2e (see Appendix A1).



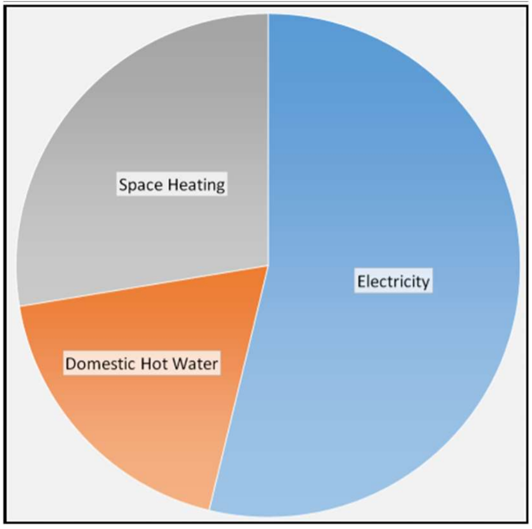


Figure 24: Energy demand (left) and GHGs (right) for a typical UK house (regulated and unregulated energy demand). Data source: Energy Savings Trust (2012).

However, in a real SAP assessment, the energy demands considered are limited to those which are *regulated*; heating, cooling, hot water, fans, pumps and fixed lighting (Department of Energy and Climate Change, 2012). *Unregulated* energy demand (anything else, for example, plug in appliances) is ignored. When this calculation method is applied to the typical UK house, the annual emissions are 1.9 tCO_2e, and space heating and hot water significantly outweigh electricity demand in terms of both energy demand and carbon emissions (see Figure 25).

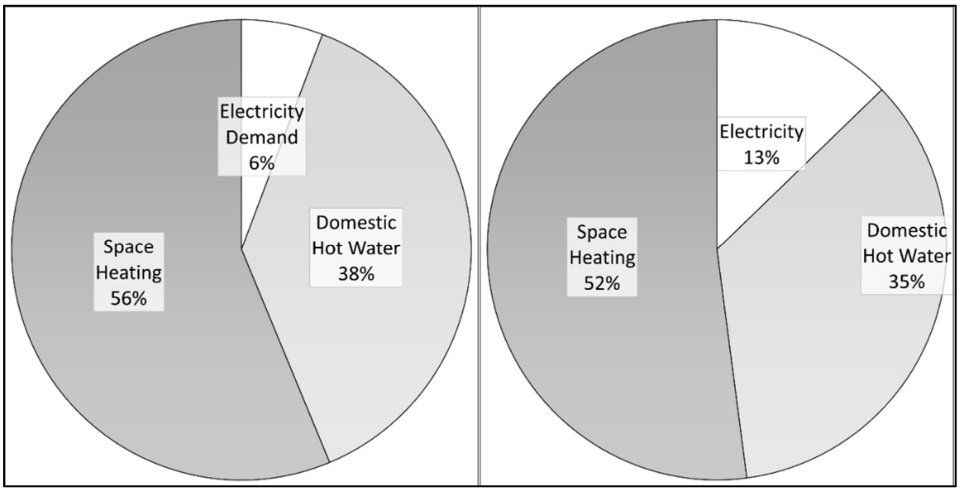


Figure 25: Energy demand (left) and GHGs (right) for a typical UK house, regulated energy demand only.

4.2. The UK's Zero Carbon Home concept

The UK's Standard Assessment Procedure for the energy rating of dwellings – SAP (Department of Energy and Climate Change, 2012) – calculates a domestic building's Dwelling Emission Rate (DER); the estimated annual carbon emissions per m^2 of floor area for the dwelling as designed. The DER accounts for energy used in heating, fixed cooling, hot water and lighting (in other words, regulated loads), and can be reduced by carbon emissions savings resulting from renewable energy generation. To contribute to reducing carbon emissions, as calculated in SAP, such renewable energy must be generated either on or in the home, on the development or through other local community arrangements (Department for Communities and Local Government, 2010).

The core requirement of a UK zero-carbon home, or Code Level 6, as defined under the Code for Sustainable Homes, is for a DER of zero (or net zero carbon emissions) (Department for Communities and Local Government, 2010). However, when the 'zero-carbon' label is being applied, the DER calculation must also account for carbon emissions arising from appliances and cooking (and so includes unregulated loads). Within this definition net carbon dioxide (CO_2) emissions is specified as:

> *(a) the annual CO_2 emissions per unit floor area for space heating, water heating, ventilation and lighting, and those associated with appliances and cooking, less*
>
> *(b) the emissions saved by the use of energy generation technologies in or on the dwelling and additional allowable electricity.*

The concept of *allowable electricity* (electricity generated from a zero-carbon energy source conveyed directly to the dwelling) was later widened to *allowable solutions* (including offsetting carbon emissions by paying into a 'green energy' fund (Zero Carbon Hub, 2011)), in order that all new homes, not just those able to connect directly to sources of wind, photovoltaic or hydro-electric power, could achieve the zero-carbon goal (Prime Minister's Office, 2014).

Within SAP, the calculation of the additional unregulated emissions is based on an assumed number of occupants; the number dependant on the total floor area of the dwelling (Department of Energy and Climate Change, 2012). This means that a greater floor area (although not necessarily footprint) needs greater renewable energy generation to offset the emissions from the additional sources of energy demand. Within a zero carbon, or energy, building concept that relies on PV generation to offset emissions or energy, the implication is that short buildings with big footprints are better than tall buildings with small footprints. Additional allowable electricity generation may come from wind, PV or hydroelectric generation, on- or off-site (Department for Communities and Local Government, 2010), as long as the contribution has not already been included in the DER calculation.

A further requirement is for any zero carbon dwelling to meet a minimum Fabric Energy Efficiency (FEE) performance (the requirement at the 7-credit benchmark under Ene2 in the Code for Sustainable Homes (Department for Communities and Local Government, 2010)). The FEE is the energy demand for space heating and cooling, and the minimum requirement depends on the dwelling type (see Table 15). The less strict requirements for detached dwellings, as opposed to apartment blocks, indicates the greater heat loss challenge faced with a large surface area to internal floor area ratio.

Table 15: Minimum FEE performance requirements to achieve zero-carbon (Code Level 6) standard under the Code for Sustainable Homes (Department for Communities and Local Government, 2010).

Dwelling Type	**Apartment blocks, Mid-terraces**	**End-terraces, Semi-detached, Detached**
Minimum FEE requirement (kWh/m^2a)	≤ 39	≤ 46

This definition of a zero-carbon home was due to become a legal requirement for all new homes built in the UK from 2016 onwards (Zero Carbon Hub, 2011). The concept was originally proposed in the 2006 Pre-Budget Report as part of the UK Government's strategy for tackling climate change (HM Treasury, 2006), and was formally codified in 2007 (Crown, 2007). The concept had the ambition that carbon emissions from all energy demand (regulated and unregulated) would be offset by renewable energy generated onsite, and allowable electricity potentially generated offsite, but directly supplying the dwelling(s). By 2008, the idea of allowable *solutions*, as opposed to allowable *electricity*, was being discussed after it was concluded that it would be impractical to achieve the original zero-carbon home definition on many sites (Zero Carbon Hub, 2011). Proposals for allowable solutions included investment in a variety of potential off-site low-carbon projects, for example, energy-from-waste plants, or low-carbon electricity generation assets remote from the dwelling site (Zero Carbon Hub, 2011).

In the 2014 Queen's Speech the UK Government announced that legislation would require all new homes to be built to a zero-carbon standard. However, instead of the original ambitious Code Level 6, the zero-carbon standard would be set at Level 5 of the Code for Sustainable Homes, with developers allowed to build to Code Level 4 as long as developments offset sufficient carbon emissions through allowable solutions to reach Code Level 5 (Prime Minister's Office, 2014). Code Level 5 requires a Dwelling Emission Rate improvement of 100% over the Target Emission Rate (TER – the SAP-calculated emission rate of a notional dwelling of the same size and shape as the real dwelling, but with specifications as defined in SAP Appendix R) (Department of Energy and Climate Change, 2012; HM Government, 2013), while Code Level 4 only requires a 25% improvement (Department for Communities and Local Government, 2010). In both cases unregulated energy demands would not be included in the calculation (see Figure 26).

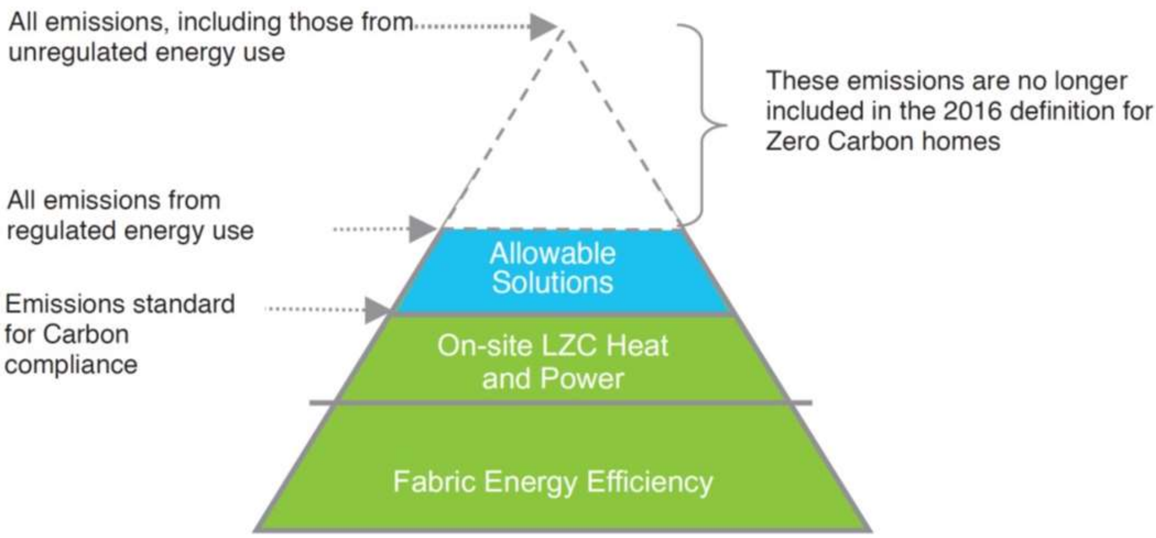


Figure 26: The 2014 planned definition for a UK zero-carbon home. Source: Zero Carbon Hub (2011).

In 2015, the UK Government announced that it did not intend to continue with either the Allowable Solutions carbon offsetting scheme, or the proposed 2016 increase in on-site energy efficiency standards (i.e. legislation for the mandatory zero-carbon home) (Crown, 2015). The explanation for this decision was outlined in the Infrastructure Bill debate:

> *The decision we have taken has balanced the cost to the development industry, particularly to smaller builders, against the wider benefits to society of energy savings and carbon reductions. Achieving that balance has to be one of our primary considerations.*
>
> *The policy question has always been about more than simply demanding that all new homes meet the highest level of carbon compliance. We also want to know whether it is realistic for the majority of builders to deliver higher standards without unduly affecting site viability or housing delivery. We all agree that we need to build more houses to solve the affordability problem, but we do not need to make building those new houses more difficult than it needs to be for the house building industry.*
>
> *…Zero Carbon Hub's report found that homes that are currently being built are not necessarily all being built to the standard they are designed to be built to. That is obviously a concern, because if developers are not able to meet current building regulation requirements, what point would there be in raising the bar even further beyond what is currently achievable on a uniform scale?*

(House of Commons, 2015)

4.3. The Passivhaus concept

The Passivhaus standard was born out of the experience of designing and building show-case, low energy homes at a reasonable cost for the German climate in the 1990s. The standard has heat loss at the centre of its philosophy, and Passivhaus buildings characteristically include high levels of insulation, including reduced thermal bridges and well insulated windows (to reduce conduction heat loss); good airtightness (to reduce heat loss through uncontrolled ventilation); and a ventilation system with highly efficient heat recovery to reduce heat loss through controlled ventilation. A dwelling's CO_2 emissions are not considered, and the Passivhaus standard is not mandatory in the UK.

The Passivhaus standard consists of five key requirements (Passive-on, 2007a):

- The useful energy demand for space heating does not exceed 15 kWh per m^2 net habitable floor area per annum.
- The primary energy demand for all energy services, including heating, domestic hot water, auxiliary and household electricity, does not exceed 120 kWh per m^2 net habitable floor area per annum.
- The building envelope must have a pressurisation test result according to EN 13829 of not more than 0.6 h^{-1}.
- The operative room temperatures can be kept above 20°C in winter using the amount of energy as defined above.
- All energy demand values are calculated according to the Passive House Planning Package (PHPP) and refer to net treated floor area (TFA), i.e. the sum of the net floor areas of all habitable rooms.

The underlying principle of a PH standard building is that all the heating or cooling required to give a high-quality thermal environment could be delivered via the fresh air needed to maintain a high indoor air quality. The PH delivered heating energy limit of 15kWh/m^2a (and 10W/m^2 heating load) is derived from this principle and is based on how much heat energy can be sensibly added to the ventilation air. The PH standard also places an overall limit on the total primary energy demand of the building, including demand for heating, lighting, hot water and electrical appliances, of 120kWh/m^{2}a.

Although the PH standard does not make direct statements about required building component specifications (e.g. U-values of walls etc.), the implications of the standard affect how the building can be built and the kinds of elements that need to be included. For the energy limit to be feasible in a northern European climate any heat energy already in the building must not be readily lost, so the heat energy demand limit is particularly focused on a 'fabric-first' approach. Table 16 shows how some of the PH requirements manifest themselves in reality.

Table 16: Passivhaus requirement and consequential building specifications

PH Requirement	**Building Specification**	**Notes**
Heat demand ≤ 15kWh/m^{2}a	Necessary U-values Opaque elements ≤ 0.15W/m^{2}K (thick insulation in walls etc.) Windows ≤ 0.85W/m^{2}K (i.e. triple-glazed windows)	Based on a design internal temperature of 20ºC, while outside temperatures may be as low as -10ºC
Heat load ≤ 10W/m^2		
Airtightness ≤ 0.6 ach @ 50pa (equivalent to approx. 3.7m^{3}hr^{-1} for a one-person dwelling at normal pressure)	Mechanical Ventilation with Heat Recovery (MVHR) necessary for ventilation (particularly in winter)	Based on an assumed ratio TFA(m^2):No. people of 35:1
Ventilation = 30m^3/hr per person		

The Passivhaus Institute have developed a detailed calculation methodology and modelling tool, known as the Passivhaus Planning Package (PHPP), which can be used in the design process to ensure the development of a building that will meet the PH standard. From a heating perspective, the model balances the estimated heat gains (including the 15kWh/m^{2}a allowed) against the estimated heat losses through the building fabric and from ventilation losses (see Figure 27). Aside from energy calculations, PHPP is also used to determine the required ventilation rates for the good indoor air quality specified by the PH standard.

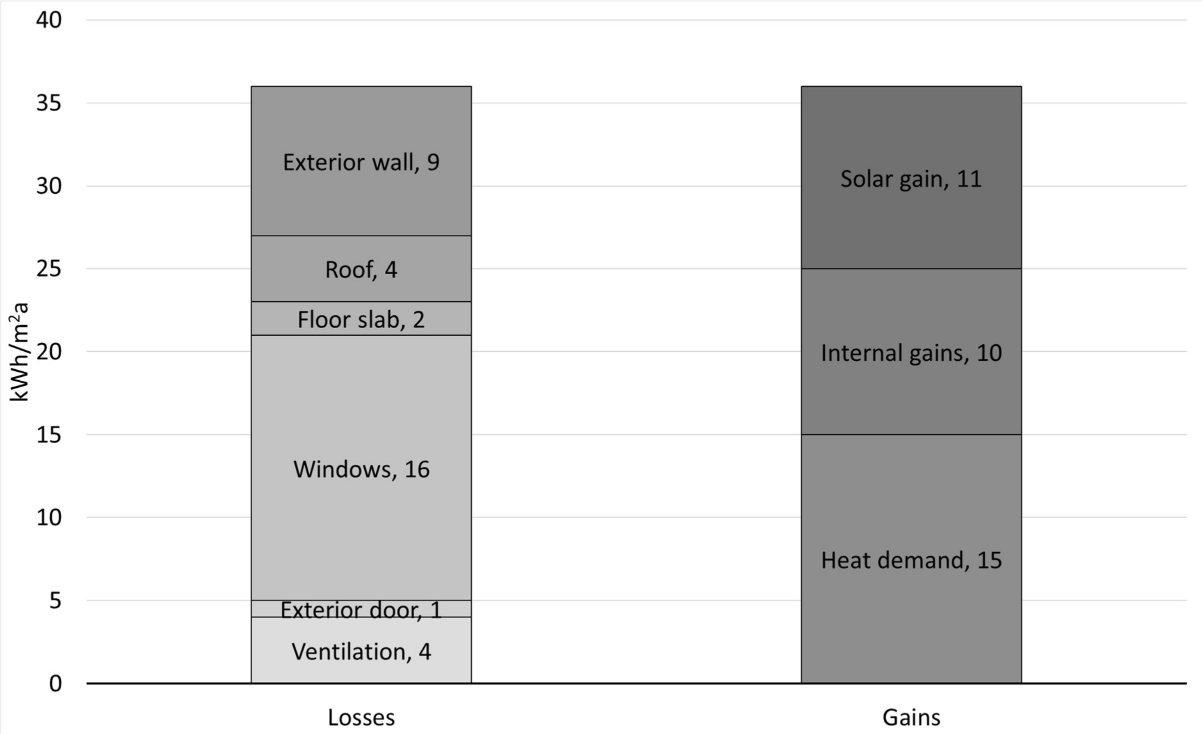


Figure 27: The balance of heat losses and gains in the Passivhaus standard. Source Cotterell and Dadeby (2012).

Although the PH standard was developed in the German climate, the PHPP model uses local climate conditions as the basis for heating demand calculations, allowing regionally specific buildings to be designed and assessed. In addition, PHPP appears to provide fairly accurate estimations of a building's real heat demand. This is a result of the detailed data required to build the model, and the rigorous quality assurance process employed during the design, construction and commissioning of a Passivhaus building. A study of 106 occupied PH dwelling units in Germany found their average actual heat demand corresponded to that estimated by PHPP (e.g. 15kWh/m^{2}a) (Cotterell & Dadeby, 2012). The range of heat demands found was attributed to different occupancy and behaviour patterns.

The two PH energy limits (15kWh/m^{2}a heat demand, 120kWh/m^{2}a total primary energy demand) are deliberately prescribed to encourage the design of buildings that use energy efficiently (Cotterell and Dadeby, 2012), rather than buildings that can produce lots of energy. In practice this means that a building with a primary energy demand greater than 120kWh/m^{2}a will not achieve the PH standard even if it produces enough renewable energy to offset this demand.

The Passivhaus Standard was designed with a view to minimising energy demand in buildings, rather than aiming to achieve zero energy through offsetting energy demanded on site with energy generated onsite or elsewhere. However, more recently, the Passivhaus Standard has been updated to account for renewable energy generated on site (see Table 17). The measure of energy generated is based on the footprint of the building, rather than the net habitable floor area. This recognises that the footprint of a building represents land that is no longer available for other uses, and that, regardless of the number of storeys a building has, a positive impact can be gained by using the resulting roof space for PV electricity generation (Krick, 2015). The new Primary Energy Renewable (PER) factor calculation encompasses the idea that renewable energy generated, but not used on site, incurs losses as a result of short- and longer-term storage (Krick, 2015). This was discussed in Section 1.5.

Table 17: Classes of Passivhaus buildings as defined using the original primary energy calculation, and the new PER (primary energy renewable) calculation. Source: Passivhaus Trust (2018).

	Classic	Classic	Plus	Premium
	Non-renewable primary energy (PE) calculation	Primary Energy Renewable (PER) calculation		
Heating demand	≤ 15 kWh/m^{2}a			
Airtightness	≤ 0.6 ach @ 50 Pa			
Entire Primary Energy demand	≤ 120 kWh/m^{2}a	≤ 60 kWh/m^{2}a	≤ 45 kWh/m^{2}a	≤ 30 kWh/m^{2}a
Entire Primary Energy Renewable Generation (in relation to projected building footprint area)	-	-	≥ 60 kWh/ m$^2_{footprint}$a	≥ 120 kWh/ m$^2_{footprint}$a

4.4. The UK Passive House concept

In response to the milder UK climate, and the perceived challenges of building to the level of quality required for the airtightness required in the Passivhaus Standard, the Passive-On project looked at developing a UK-specific dwelling design that would still fulfil the Passivhaus energy and comfort criteria. This still required an indoor temperature of 20ºC in the winter, but with UK temperatures rarely falling to -10ºC, the performance of the UK Passive House’s thermal envelope did not have to match that of a normal Passivhaus building.

At the time of the development of the UK Passive House design, the (Classic) Passivhaus requirements did not include renewable energy generation, so the UK Passive House concept includes no renewable energy generation criteria. Table 18 shows a comparison of the envelope requirements for a Passivhaus in the UK (Pelsmakers, 2012), a UK Passive House (Passive-on, 2007b) and a notional dwelling as defined in UK Building Regulations (HM Government, 2013).

Table 18: Comparison of thermal envelope requirements (maximum U-values) for building elements complying with different building standards for a house built in Birmingham, UK (the weather file used to represent the UK in the Passive-On project).

	Max. U-value (W/m^{2}K)			
Building Element	**UK Building Regs (2006)**	**UK Building Regs (2014) Notional dwelling**	**UK Passive House (design based on an upgrade to UK 2006 Building Regs)**	**Passivhaus (recommended U-values for space heat demand limit)**
Walls	0.30	0.18	0.15	0.15
Exposed floors	0.25	0.13	0.20	0.15
Roofs	0.20	0.13	0.20	0.15
Windows, doors, roof lights	2.00	1.40	1.80	0.80

The UK Passive House design is for a 'typical' three-bedroom end of terrace house (see Figure 28). It is rectangular in shape with two floors and a pitched roof. The ground floor is open-plan and, as part of the 'passive' heating and cooling strategy, incorporates a glazed buffer zone at either end of the house. Some detail of the configuration and materials of building elements are provided (Passive-on, 2007b), but overall building dimensions are not given. However, an average three-bedroom semi-detached house in the UK has 88m^2 useable floor area (Department for Communities and Local Government, 2013). No renewable energy generation technology is included in the design.

Figure 28: Image, section and plan of the UK Passivhaus. Source: Passive-on (2007b).

4.5. Questions arising from ZeroCC concepts

The fact that the UK Passive House is designed to achieve Passivhaus requirements in the UK raises the question of how the performance of such a building should be measured. Both the Standard Assessment Procedure (SAP), which is used to assess the performance of domestic buildings in the UK, and the Passivhaus Planning Package (PHPP), the Passivhaus Institute's calculation methodology, are concerned with the direct (site, or delivered) energy demand associated with heating (in terms of kWh/m^{2}a). As discussed previously this is a measure of how well the building envelope resists the movement of heat through it, and to a degree the temperature difference between inside and out.

However, the two assessment methodologies diverge in their view of a domestic building's overall energy demand (including heating – which is more significant in colder climates).

SAP concentrates on carbon emissions (in the form of the Dwelling Emission Rate – DER) calculated from the delivered energy demand and the carbon intensities (CIs) of the relevant sources of energy. PHPP is instead concerned with the building's primary energy demand, based on delivered energy demand and the primary energy factors associated with the relevant sources of energy. SAP allows the DER to be reduced by allowable solutions – e.g. PV generated electricity which is assumed to offset electricity demand on a one-for-one basis. The classic form of the Passivhaus assessment does not allow for renewable energy generation offsetting at all. The updated Passivhaus assessment does allow for offsetting, but any renewable energy primary energy factors are reduced to account for losses incurred during the storage of surplus energy (as discussed earlier in Section 1.5).

A common thread running through the ZeroCC definitions is the need for a mechanism whereby carbon emissions or energy demand can be offset. Given energy generation is the main cause of carbon emissions globally (IPCC, 2014) (see also Figure 1), and buildings are responsible for a large proportion of electricity demand (66% of electricity consumption in the UK (Committee on Climate Change, 2018b)), it is not surprising that the focus of offsetting in building codes is 'zero-carbon' or renewable energy generation, often in the form of PV electricity generation (Parkin, et al., 2015; Voss & Musall, 2013; Department for Communities and Local Government, 2010). Such offsetting relies on the idea that a unit of renewably generated energy is 'worth' the negative equivalent of the same amount of energy generated through traditional (carbon intensive) means. For example, the UK's Standard Assessment Procedure (SAP), which is used as the basis for calculating the energy demand and/or carbon emissions associated with UK buildings, determines that one kWh electricity drawn from the national grid is worth 0.519 kg greenhouse gas emissions (measured in terms of the carbon dioxide equivalent – CO_2e) (Department of Energy and Climate Change, 2012). A corresponding kWh generated by PV is therefore worth minus one kWh, when measured in terms of energy, or minus 0.519 $kgCO_2e$, when measured in terms of carbon (or greenhouse gas emissions).

The European Union (EU) has recognised that, as direct combustion of fossil fuels is necessarily reduced, greater sources of renewable energy will be needed (European Parliament, Council of the European Union, 2009). It is estimated that by 2050, electricity will cover around 50% of European energy needs (compared to 25% currently) (EURAMET, 2018), and that by 2030 between 15% and 25% of European electricity will be produced from solar energy (European Photovoltaic Industry Association, 2012). Rooftop photovoltaic installations are expected to dominate the European market in the short term, and it is estimated that there is sufficient space on buildings to generate more than 30% of current European energy needs (El Gammal, 2016).

In the developing world, throughout rural parts of South Asia and Africa, PV-battery installations, also known as mini-grids, are increasingly seen as one of the most promising ways to connect the 1.1 billion people in the world who still lack access to electricity (The Economist, 2018; The Economist, 2016). These mini-grids consist of a bank of batteries, charged by PV, connected to homes to provide 24-hour power independent of the national network. The motivation behind the development of such systems is more closely associated with the economic benefits that reliable electricity can bring, rather than climate change concerns. However, mini-grids provide a method of energy generation which would otherwise be realised through fossil fuel combustion (i.e. diesel, kerosene, coal- and gas-fired electricity). In locations where populations, and people's demand for energy, are expected to grow significantly over the coming decades (see Figure 11), replacing reliance on fossil fuels with access to renewable energy is beneficial from the perspective of reducing carbon emissions, despite the initial economic driver.

The implication of offsetting via renewable energy generation is that if a UK building generates as much energy as it needs to satisfy its demand, it can be classified as a net zero energy building. If the energy in question is electricity (both demand and generation), the building can also be classified as a net zero carbon building, assuming the electricity carbon intensities as described above and in SAP. This is a logical, but simple paradigm, and more detailed analysis of the ZeroCC concept raises a number of questions:

- For the renewable energy to count in the demand-generation balance, must the method of energy generation be physically part of the building? If not, how far away can it be?
- Must the renewable energy generated be used exclusively by the building generating it? Or can the renewable energy generated be exported to a wider energy grid from which the building can draw energy at a different time?
- How can the balance be calculated if different types of energy are used in the building? For example, the carbon intensity of UK gas, typically used for heating UK homes, is 0.216 kgCO_2e per kWh (Department of Energy and Climate Change, 2012).
- What if carbon intensities change over time?
- Given energy is needed to manufacture renewable energy generating technology, is it realistic to treat the energy generated as ‘free’, or carbon-free?
- What about the energy demand, or carbon emissions, associated with constructing the building in the first place?

4.6. Postscript

This Chapter has looked at ZeroCC concepts that have been applied to UK dwellings. The final two questions raised at the end of this Chapter, and the comparison of the two schools at the end of Chapter 3, highlight the important issue of embodied carbon and energy. This is an emerging area of interest in the ZeroCC landscape which is rarely addressed in established ZeroCC concepts. Chapter 5 therefore looks in detail at this topic and identifies the many complexities that lie within it.

Chapter 5 starts by defining what embodied carbon and embodied energy are, and goes on to describe the different methods that have been used for their measurement. Attempts that have been made to incorporate these issues into ZeroCC building concepts are described, and the often-overlooked subject of carbon embodied in photovoltaic systems is discussed.

Chapter 5. Embodied carbon and embodied energy

Embodied carbon (EC) and embodied energy (EE) are measures of the carbon emissions or energy embodied in the fabric of a building, or manufactured products. These metrics can be measured respectively in terms of $kgCO_2e$ and kWh per quantity of product (e.g. per brick; per kg of cement; per m^2 of PV; per m^2 of building floor area).

The Inventory of Carbon and Energy (ICE) (Hammond, et al., 2011) defines embodied energy (and carbon) as

> *the total primary energy consumed (carbon released) from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate.*

The specific nature of this definition highlights the fact that accounting for the EE/EC in a building is to a certain extent a matter of determining boundaries. A calculation of EE that only went as far as totalling the ICE's EE of the components of the building would neglect to recognise the effects of transportation to the site and assembly of the components. This bottom-up method of determining the EE of a building is known as the 'process' method, and can be contrasted with the top-down 'input-output' (I-O) method that tries to ensure all EE connected to the delivery of a product is accounted for.

This Chapter describes the different approaches that have been taken to measuring embodied energy and carbon. It also considers the difference between assessing embodied energy and embodied carbon and discusses the idea that embodied carbon can be negative (and therefore contribute to reducing carbon emissions from buildings).

5.1. Measuring embodied carbon and energy

It has been previously estimated that the embodied energy (EE) associated with a building is far less than the energy required to run it over its lifetime. Improving energy efficiency in buildings has therefore been seen as a greater priority (Cotterell and Dadeby, 2012). However, it is understood that, as energy performance does improve, EE will account for an increasing proportion of the overall environmental cost of the building (Ibn-Mohammed, et al., 2013; Hamilton-MacLaren, et al., 2009). Indeed, in a recent research commission, looking into the cost-effectiveness of new lower-carbon and energy buildings, the CCC included a request to examine approaches to incorporating embodied carbon in standard setting (Committee on Climate Change, 2018b; Crown, 2018).

The challenge faced by the construction industry is that there are no agreed measurement standards to deal with the issue of embodied energy or embodied carbon (EC). Life Cycle Assessment (LCA) provides an internationally accepted method for investigating the life impact of a product or system (BS EN 14040, 2006), but the scope is often much wider than just energy use, and what is included in the analysis (the boundaries) is down to the person carrying out the study. Results are only comparable if the same boundaries are used to analyse products that perform the same function. However, given the variety in building projects (type, size, location, design life, etc.) general LCA allows for very limited comparability. A specific LCA standard for construction projects exists (BS EN 15978 , 2011), but even within this there is no guarantee of absolutely consistent application. For example, BS EN 15978 allows the assessor to subjectively estimate the number of times building components are replaced during the lifetime of the building being assessed. The Green Guide (BRE, 2019) provides environmental impact (alphabetic) ratings for a number of defined building element type specifications, based on an LCA methodology, which are referred to in the Mat1 element of the Code for Sustainable Homes assessment – and form part of the original UK Zero Carbon Home assessment.

5.2. Life cycle assessment

Life cycle assessment as a methodology has been developing since the late 1960s, and is used for the determination of the environmental impact of a product or system over its whole lifetime (Buyle, et al., 2013). Initially life cycle studies focused on the quantification of materials and energy used, and waste products released throughout the lifecycle, but as the concept developed consideration was also given to all associated environmentally relevant inputs and outputs. Although there are now international standards for carrying out and documenting LCAs (BS EN 14044, 2006; BS EN ISO 14040, 2006), the methodology is still quite flexible so that it can be adapted to the context and purpose of a specific study. Three main LCA types can be identified which have slightly different objectives. Stand-alone LCAs are used to explore important environmental characteristics of a single product, and are therefore not applicable to the comparison of buildings. Accounting LCAs are used to compare existing products, and consider what environmental impact can be associated with each product. Change-oriented LCAs again compare products, but this time the goal of the study is to provide information for decisions about products to be developed in future. More recently BS EN 15978 (2011), the European standard for the assessment of the environmental performance of buildings, was published. Whichever type of LCA methodology is followed there are some fundamental elements which are common to them all. Based on the guide to LCA provided by (Baumann & Tillman, 2004) these are summarised below in Section 5.2.1.

5.2.1. LCA methodology

LCA is a fairly involved process requiring many decisions and the collection of substantial amounts of data. As previously stated, the outcome of an LCA is very much dependent on the particular methodology followed, and this in turn is determined by the initial objective identified by the commissioner of the study. A goal must be decided upon; this is essentially the question that needs to be answered (e.g. what is the environmental impact of product A?). A scope needs to be defined; this determines how that question will be answered. It is normal for an LCA to be an iterative process, for example it may be necessary to modify the objectives as a result of the availability of data, but ideally the goal and the scope will be defined early on. These two core aspects of the LCA process require decisions to be made on the definition of the functional unit; the impact categories and the impact assessment method; the system boundaries and the principles for allocation; and the data quality requirements.

The functional unit needs to be quantitative, and, in the case of comparative studies, must represent the function of the compared options in reasonably fair way. Examples of functional units include litres for drinks packaging; person x km for passenger transportation; kg clean laundry for detergents. Energy use in buildings is usually measured in units of kWh/m^2 floor area.

The impact categories chosen determine the inventory data that needs to be collected, and the impact assessment choice determines how that data is interpreted. For example, the impact category ecological consequences may be interpreted in terms of global warming or alternatively in terms of acidification. These two consequences are measured using different metrics and, therefore, require access to different data.

System boundaries determine what is included in the LCA, and what is left out. It is therefore important to select appropriate boundaries in order that the outcome of the LCA reflects reality. Boundary considerations may include determining where the life cycle begins and ends (e.g. cradle-to-grave vs. cradle-to-gate); the geographical limitations of the study (for example, methods of electricity production vary across countries); the time perspective (change-oriented LCAs are prospective and may require assumptions about future waste treatment methods, while accounting LCAs are retrospective); and technical system boundaries (whether or not the environmental impact from production and maintenance of capital goods should be included). In addition, the processes involved in the life cycle of the product under investigation may be shared with those of other products, and in this case the environmental impact needs to be allocated between the different products. For example, one product may be recycled into another product and the impact associated with each product separately may need to be determined.

The quality of the data used will influence the view of reality that the outcome of the LCA presents. Data should be relevant, reliable and accessible. Relevance refers to the extent to which the data collected is representative of the product or system under investigation. For example, an old set of data may not be representative of a current situation. The reliability of data will be dependent on its numerical accuracy and uncertainty, as well as the consistency with which it has been collected. Finally, data which is transparently documented and can be accessed and reviewed by other people will give the LCA outcome greater credibility.

It is clear from the above that the many options available to an LCA analyst in setting up the study mean that each study is almost unique. LCAs are resource intensive, and studies carried out by different analysts are unlikely to yield easily comparable results.

5.2.2. Construction specific LCA

LCA was originally developed within the realms of marketing and strategic development for individual manufactured products, and its complexity even at this level makes LCA an unwieldy tool for application to the much more multidimensional life of a building (Buyle, et al., 2013). In addition, it has been a past criticism of LCA that, in its ability to be tailored to the objectives set by the commissioner of the study, its outcome may be moulded to the interests of the commissioner, showing the product under investigation in a more (or less) favourable light than is really justifiable. However, the principles behind LCAs form a logical and tested framework, and the BS EN 15978 standard provides a building-specific LCA methodology. Although this still retains some of the complexity and flexibility inherent in LCAs in general, the standard sets out the specification of certain boundary conditions, including how to deal with issues surrounding the maintenance and replacement of building components. While it provides some useful principles, there is still a requirement for assessors to make some subjective judgements. For example, the determination of the number of times a component may be replaced is based on the ratio of the design life of the building to the expected life of the component, but the assessor can decide to assume that the final replacement may not occur, depending on what the component is and how close the final replacement would be to the end of the design life of the building (BS EN 15978, 2011). Another problem, related to simplicity and comparability, is that the output of the calculations results in a number of environmental impact indicators for which there is no method of aggregation. This means that the results of the study would still need to be interpreted in light of the context of the study and the definition of the function of the 'object of assessment'.

5.3. Embodied energy calculation methodologies: Process, Input-Output (I-O) and Hybrid

As mentioned above, the process method of calculating the embodied energy of a building essentially sums the EEs of all the components in the building. This method requires access to a comprehensive database, such as the ICE (Hammond, et al., 2011), which details the EEs of the relevant materials and components. (Proietti, et al., 2013; Himpe, et al., 2013; Culakova, et al., 2012) provide examples of this method being used to estimate the EE of buildings. The approach incurs a truncation error as the boundaries of the calculation do not always account for energy inputs high up in the supply chain, or in related supply chains (e.g. indirect energy inputs), resulting in an underestimation of the EE of a building (Stephan, et al., 2012). It can also be difficult to make comparisons between the results of studies, such as those referred to above, since different boundaries have been used in the calculations.

An alternative method is to base calculations on the energy intensities of relevant economic sectors. (Acquaye, et al., 2011; Acquaye & Duffy, 2010) demonstrate how input-output analysis techniques can be used to determine national energy intensities per monetary unit (i.e. how much energy is consumed for each pound spent in that sector). These energy intensities can then be multiplied by the prices of building materials and components to give an estimate of the total EE of the building. While this technique will account for all the direct and indirect energy inputs, its accuracy is limited by aggregation errors, as all components from the same economic sector will have the same energy intensity (Stephan et al., 2012). Improved accuracy can be achieved by combining these two approaches into a hybrid method as detailed in (Stephan, et al., 2013a; Stephan, et al., 2012; Acquaye, et al., 2011). Here a process approach is taken where the EE data is available for materials and components, and the I-O approach is used for elements of the project that are more difficult to define from an EE perspective (e.g. energy used for setting up the site).

Moncaster and Symons (2013) created a whole life embodied carbon and energy of buildings (ECEB) tool based on the requirements of BS EN 15978 designed for early design stage decisions, and applied it to a simple masonry dwelling. One of the main conclusions drawn was that lack of available data is a significant challenge to the implementation of BS EN 15978. This is principally because the standard requires a process approach to the calculation of EE and EC, and, as a result, some fairly significant assumptions needed to be made. For example, the calculation of the EC of all the windows in the building, regardless of size, was based on the EC per m^2 of one $2m^2$ window, and windows themselves are complex elements to analyse (see discussion in Appendix A2). While the limited accuracy of this method is acknowledged, it is explained that the alternative input-output (I-O) approach may not fairly represent 'green' building materials and components as they tend to be relatively more expensive.

The ICE Domestic Building Model (DBM), developed using the ICE database, provides a range of estimates of the EC for particular domestic building specifications (Hammond & Jones, 2009). A 'typical' semi-detached house is estimated to have an EC of 425 $kgCO_2/m^2$. This value includes the building envelope as well as foundations and internal finishes. The authors make clear that the relationship between EC and floor area is not linear, so buildings of different sizes will normalize to give very different estimates. Additionally, Hammond and Jones note that, because different manufacturers may use different fuel combinations in their production processes, the determination of the EC of manufactured products (as opposed to homogeneous materials) is difficult. Despite this limitation, the DBM clearly indicates that the glazing component of a building accounts for a very large part of its total EC (around 20%).

5.4. Embodied energy comparisons in low energy buildings

While LCA has been used widely as a research methodology, direct comparisons between studies are almost impossible as a result of the variety of boundaries that may be set, and data that may be used. There are, however, some themes that can be identified. In a review of 38 previous LCA studies in the construction sector it was concluded that most studies, particularly the earlier ones, concentrated on energy, rather than other environmental aspects (Buyle, et al., 2013). There was also a general consensus that, although comparability between studies, or even buildings, is difficult given the varying boundaries (lifetimes, levels of detail, etc.), the operational part of a building's life is the dominant part of the life cycle impact. A separate review of another 60 previously reported case studies, looking at the life cycle energy use of both conventional and low-energy buildings came to the same conclusion (Sartori & Hestnes, 2007). It was therefore suggested that operational energy should be the area tackled first in reducing energy consumption, even though doing so tends to require increased use of (usually energy intensive) materials, and so embodied energy (EE). The work also highlights the general inconsistency with which the energy requirements associated with a building are defined. The operating energies reported (which may relate to heating only, or a variety of uses) were a mixture of delivered and primary energy values, and the EEs reported could consist of EE from construction (initial EE), that associated with maintenance (recurring EE), so called feedstock EE (the calorific energy in the materials), or a mixture of the three.

The importance of the embodied energy in the life cycle of a building depends largely on how, and over what period of time, the embodied energy is measured. There appears to be no agreed measurement standard to deal with this issue, and consequently different studies use different measures, resulting in different conclusions being drawn. It has been suggested that the process method of calculating EE may significantly underestimate EE values (Moncaster & Symons, 2013; Stephan, et al., 2013a). A different view on the relative importance of EE in the life cycle of a building was reached when the hybrid I-O approach was used (Stephan, et al., 2012). Two very low energy buildings were compared; an Australian 7-star house and a Belgian passive house. It was found that EE accounts for a substantial amount of life cycle energy demand in both these cases. In relation to EE (initial and recurring) and operational energy over a 50 year period EE amounted to 45% for the Australian house and 59% for the Belgian house. Reported separately, the EE for the Belgian house rises to 77% over a 100 year period (Stephan, et al., 2013a).

Stephan et al. (2013a), using the hybrid I-O approach, also notes that the total (lifetime) energy consumption of a new standard house and a passive house are very similar, and puts this down to the payoff between the higher EE, from greater insulation levels, and the lower operating energy needed by a passive house as compared with a standard house. In the case of the standard house, over a 100 year period, EE amounted to approximately 42% of the total energy demand (EE and operational). A similar conclusion was drawn in a life cycle study that used the process approach to analyse a Perugian Passivhaus (Proietti, et al., 2013). Conversely, another process based, but more in-depth, LCA using a different low-energy Belgian house for comparison suggests that the higher heat demand of standard houses, compared with low-energy houses, leads to the need for more materials (and higher EE) in order to provide sufficient heating services (Himpe, et al., 2013), so balancing out the higher EE associated with a passive house construction. The different locations of these houses raises the important contextual issue of climate that needs to be addressed when assessing low energy buildings, particularly where heating systems are concerned.

5.5. Embodied carbon vs. embodied energy

Embodied carbon and energy are linked, but are not necessarily interchangeable. Different manufacturers may use different fuel combinations in their production processes, or different production processes altogether. In addition, embodied energy values quoted in literature are often reported in terms of primary energy. As primary energy factors vary by fuel and across countries, the embodied energy of a product from one manufacturer may be different to the embodied energy of the same product from a different manufacturer, and neither value may be readily translated into an embodied carbon value. This can be illustrated in the simplified example of baking a cake.

Assume the power required to keep an oven at a temperature suitable for baking is 1 kW, and the time required to bake a cake is one hour. The total 'site' energy required to bake the cake is therefore 1 kWh. However, the resulting primary energy demand depends on the fuel used to power the oven; 3.07 kWh for an electric oven, 1.22 kWh for a gas oven (using UK primary energy factors from SAP (Department of Energy and Climate Change, 2012)). Similarly, the carbon emissions associated with baking the cake vary with the fuel used; 0.519 $kgCO_2e$ if electricity, 0.216 $kgCO_2e$ if gas (also from SAP).

If a zero energy building concept sets the boundary at the site, 1 kWh of site generated PV electricity is sufficient to offset the energy demand of baking the cake, regardless of the type of oven used. However, if the boundary is widened to include primary energy, less site generated PV electricity is needed to offset the primary energy demand of baking the cake in a gas fired oven (only 0.4 kWh). This is because PV generated electricity has a primary energy equal to the electricity grid to which it is connected, but negative (i.e. -3.07 kWh in this example). Therefore, to offset the energy needed to produce the same cake requires different amounts of PV generated electricity depending on whether measurements are made in terms of site energy or primary energy, and the type of oven used. A further consideration raises the issue that, while PV generated electricity may be assumed to flow in and out of the electricity grid as required, and can therefore be seen as offsetting the electric oven energy demand, a gas oven cannot be powered by electricity. To bake the cake in a gas oven will always require energy/fuel to be drawn from the gas grid regardless of the amount of any PV generation.

Where carbon emissions are the metric used, the direct environmental impact of baking the cake is evident. Similar to the case with primary energy measurements, the actual energy needed to bake the cake is hidden behind the carbon intensity of the fuel used, but the offsetting philosophy is perhaps more logical. Carbon emissions arise as a result of baking the cake, regardless of the oven type, but carbon emissions can be prevented by substituting grid electricity with PV generated electricity. Under this zero carbon concept it is the impact on climate change from fuel consumption and PV generation that must cancel out. In the case described here less PV electricity is still needed to offset the baking if a gas oven is used.

As an object with embodied energy and carbon properties the cake may be described as having an embodied *site* energy of 1 kWh. This is a good indication of the energy required to bake the cake (and, to some degree, the performance of the oven used). Alternatively the cake may be described as having an embodied *primary* energy of 3.07 kWh or 1.22 kWh, depending on the type of oven used. This metric describes the energy needed to bake the cake along with the performance of the oven as connected to its energy grid (electric or gas). However, without knowledge of the oven type used, it is difficult to make comparisons between the outcomes of baking. For example, two cakes could be baked in succession in the gas oven for less primary energy than is required to bake one cake in the electric oven. This is not because the gas oven works better than the electric oven, but because of the differences in the properties of the energy grids which the ovens are connected to.

The cake may also be described as having an embodied carbon of 0.519 $kgCO_2e$ or 0.216 $kgCO_2e$, depending on the oven type used. As with the primary energy metric, knowledge of the oven type used would be needed to translate the embodied carbon into embodied site energy. However, it is arguable that, where climate change is concerned, what is important is not the amount of energy that is needed, but the carbon emissions that arise from generating the energy. The embodied carbon metric gives a direct indication of the emissions associated with the cake.

5.6. Negative embodied carbon

While the embodied carbon of most construction materials is positive, some materials can be viewed as having a negative embodied carbon (although the embodied energy will always at best be zero). The growing process of organic materials such as timber and straw sequesters carbon dioxide. Where significant quantities of such materials are used in the construction of a building, the sequestered carbon may offset the positive embodied carbon of other materials, potentially leading to an overall negative building embodied carbon (for example the school building in Bath described at the end of Chapter 3 (Pelly & Mander, 2014)). However, the carbon sequestration properties of timber are not universally accepted as appropriate for use in a zero carbon building strategy. The Inventory of Carbon and Energy points out that, if timber is being consumed faster than it is grown, it is unrealistic to view the use of timber products as having a net global positive impact on carbon emissions (Hammond, et al., 2011). Equally, in the case of unsustainably sourced timber, deforestation has the effect of actively contributing to carbon emissions (Weight, 2011).

The use of straw as a negative embodied carbon building material is less controversial; it grows quickly and is a bi-product of food production (Sodagar, et al., 2011). Straw bales have been used successfully in a number of commercial construction projects in the UK with reported carbon sequestration of -1.35 $kgCO_2e$ per kg of straw (Sodagar, et al., 2011). From an operational perspective, straw also has beneficial insulating properties with reported straw bale U-values of 0.13 – 0.19 W/m^2K (Thomson & Walker, 2014).

5.7. Embodied carbon in renewable energy generation

There is clearly value in the use of PV in a zero carbon building concept. The renewable electricity produced by the PV offsets the electricity that the building would otherwise demand from the national electricity grid. When this is translated into equivalent emissions of carbon dioxide (CO_2) the traditional view is that one kWh of PV-generated electricity effectively saves the CO_2 emissions that would be caused by the generation of one kWh using the normal electricity grid. In the UK grid-generated electricity emissions are measured at 0.519 $kgCO_2/kWh$ (Department of Energy and Climate Change, 2012), so in a carbon balance one kWh PV-generated electricity counts as -0.519 $kgCO_2$. Therefore, PV-generated electricity is a useful tool to reduce the overall carbon emissions of a building, potentially to zero (Parkin, et al., 2015). However, the carbon balance described above sets the boundary of the calculation around the operation phase of a building's life and ignores the carbon emissions that arise from the production of the means to generate the electricity.

Both the construction of traditional centralised power stations and the production of PV modules result in carbon emissions. However, while the majority of carbon emissions from the life of a power station tend to come from the burning of the requisite fuel, rather than the construction of the facility, the opposite is true in the life of a PV module (Fthenakis & Kim, 2011). Figure 29 shows a comparison of the 'front end' (before energy generation starts) and 'operational' emissions in the lifecycle of a number of energy producing systems.

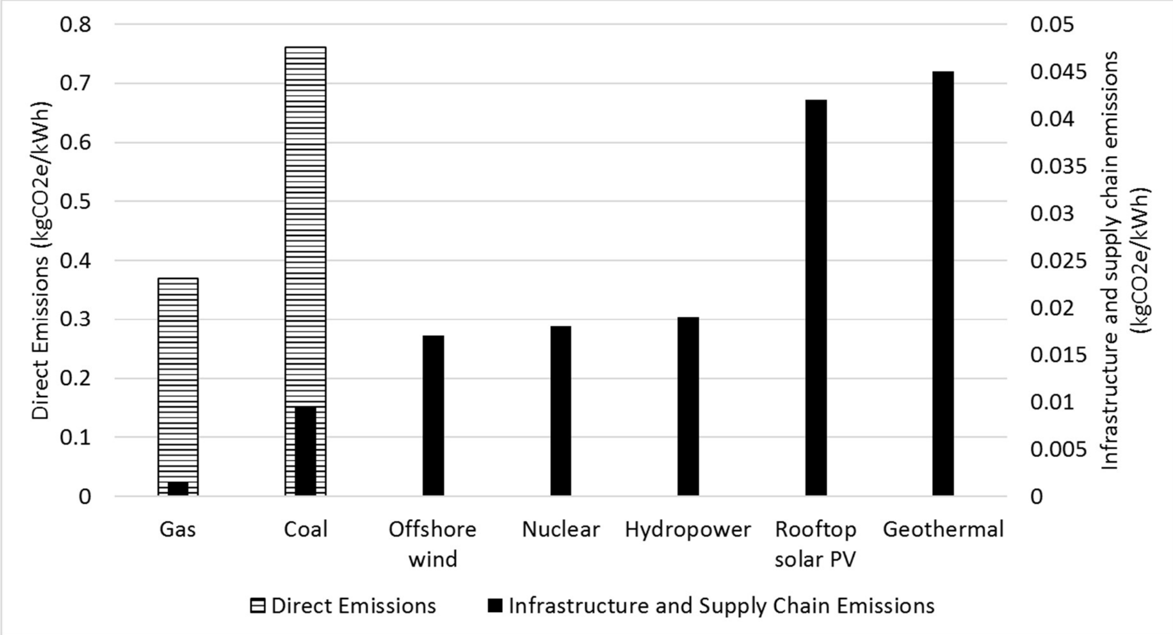


Figure 29: Comparison of direct carbon emissions and infrastructure and supply chain carbon emissions associated with different energy generation technologies. Source: Marcus (2017) using on data from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Schlomer, et al., 2014).

When considering the lifetime carbon emissions of PV in a zero carbon building, the assumption that PV-generated electricity exactly displaces the carbon emissions of grid-generated electricity is an oversimplification. For a lifetime zero carbon building concept, that covers operational and embodied carbon in its metric, it is necessary to be able to factor in both the carbon benefits and the carbon costs of including PV in the building design.

To determine the lifetime carbon cost and benefit of a PV module requires appreciation of the carbon emissions that result from the production of the PV module, as well as the carbon emissions that are prevented by the electricity generation of the PV module. The former emissions will vary between countries, depending on the carbon intensity (CI) of each country's manufacturing energy grid (measured in $kgCO_2/kWh$), and with different manufacturing processes (Mann, et al., 2014; Fthenakis & Kim, 2011). The latter will also vary between countries, depending on the carbon intensity of each country's electricity grid and the available insolation (Nawaz & Tiwari, 2006), but additionally will vary with the efficiency of the PV module and the lifetime over which it can generate electricity.

Traditionally, PV modules are optimised, selected and sold on the basis of power produced under standard test conditions (1000 W/m^2 (BS EN 60904-3, 1993)). However, it has been acknowledged that this metric does not always reflect real-world conditions, and location dependent variations in ambient temperature, irradiance, angle-of-incidence, spectrum and wind-speed cause deviations in annually-averaged module generation (Biyik, et al., 2017). Not only does this contribute to a proportional financial risk to return on investment, but also to a climate change risk return on investment. Much research has been undertaken looking at the environmental benefits and costs of PV electricity production (Mann, et al., 2014; Fthenakis & Kim, 2011; Sherwani, et al., 2010). However, these studies have been conducted in various locations around the world, using different PV modules, manufactured in different countries, and exposed to different amounts of sunlight. Rarely is a stated value for the embodied carbon of the PV modules under investigation given, so no direct comparison on that basis can be made. Instead, in attempting to assess the benefit of PV in a consistent manner, most of the published data is reported in terms of the following metrics:

- The overall carbon intensity (CI) of the electricity generated by PV ($kgCO_2e/kWh$) (Sherwani, et al., 2010; Fthenakis, et al., 2008) This is a measure of the carbon emissions caused by the manufacture of the PV and the amount of PV-generated electricity, and can be easily compared with the CI of a national electricity grid;

- The energy payback time (EPBT), measured in years, of the PV (Mann, et al., 2014), which can be used to compare the efficacy of different PV systems;
- The energy return on investment (EROI) (Dutil & Rousse, 2012). This is another mechanism for comparing PV systems, but based on the total amount of energy (kWh/m^2_{PV}) required to produce, and generated by, the PV.

Unfortunately, all of these metrics are subject to the variations in location and efficiency as described above, so it is not possible to use this information to work backwards and calculate comparative values for the embodied carbon cost of these PV modules. For example, using data presented in Fthenakis and Kim (2011) a CdTe PV module in the USA can be estimated to have an embodied carbon of 70 $kgCO_2e/m^2_{PV}$. However, the embodied carbon of the same type of module with a similar efficiency (8%) and same lifetime, but located in Germany, can be calculated to be 37 $kgCO_2e/m^2_{PV}$. The former embodied carbon value is based on a PV module CI of 0.018 $kgCO_2e/kWh$; an assumed average insolation of 1,800 kWh/m^2a; a PV module efficiency of 9%; a performance ratio of 0.8; and a PV module lifetime of 30 years. The latter value is based on a PV module CI of 0.012 $kgCO_2e/kWh$; insolation of 1,700 kWh/m^2; and a performance ratio of 0.75 (Fthenakis & Kim, 2011). See Appendix A3 for the calculations. The different levels of insolation the PV modules are exposed to may account for the differences in their CI values, but so too may their place and manner of manufacture (USA electricity CI = 0.613 $kgCO_2/kWh$, while the average European electricity CI = 0.353 $kgCO_2/kWh$ (MacKay, 2009). The research published does not provide any explanation for this difference in CI values.

A review of PV life cycle assessments, (Sherwani, et al., 2010) cites two studies with similar findings. The first, involving KC120 multi-crystalline modules, reported life CO_2 emissions of 0.072 $kgCO_2e/kWh$ and 0.055 $kgCO_2e/kWh$ for PV under US conditions and European conditions respectively (Pacca, et al., 2007) cited in (Sherwani, et al., 2010). The second reported on CO_2 payback time differences connected to the locations of manufacture and use of multicrystalline silicon modules (Komiyama, et al., 1996) cited in (Sherwani, et al., 2010). Those manufactured and used in Japan had a payback time of 8.04 years, compared with 3.91 years for those manufactured and used in Indonesia. The case where the modules were manufactured in Japan but used in Indonesia was also investigated and a CO_2 payback time of 3.37 years was reported. The outcomes from all these studies suggest that the same PV module may be more or less beneficial, with regard to climate change, depending on where, and how, it is manufactured and where it is sited for generation purposes.

It is not easy to pin down a current general embodied carbon value for PV modules. However, there are a number of sources of information which provide some guidance as to what may be a reasonable figure to use in a zero carbon building concept. These are summarised in Table 19.

Table 19: PV embodied carbon values from literature (ordered by source year of publication).

Source	Module type	Stated value (per m^2_{PV})	Location of manufacture	Assumptions	Embodied carbon value ($kgCO_2e/m^2_{PV}$)
Mann et al., 2013	Multi-crystalline silicon	2,150 $MJ_{primary}$	Europe	European primary energy factor = 0.315 European electricity EI = 0.617 $kgCO_2e/kWh$	116
Mann et al., 2013	Mono-crystalline silicon	2,750 $MJ_{primary}$	Europe	European primary energy factor = 0.315 European electricity EI = 0.617 $kgCO_2e/kWh$	149
Hammond and Jones, 2011	Poly-crystalline silicon	1,945 to 5,660 $MJ_{primary}$	UK	Typical UK industrial fuel mix used for manufacture	99 to 289
Hammond and Jones, 2011	Mono-crystalline silicon	2,590 to 8,640 $MJ_{primary}$	UK	Typical UK industrial fuel mix used for manufacture	132 to 440
Hammond and Jones, 2011	Thin film	775 to 1,805 $MJ_{primary}$	UK	Typical UK industrial fuel mix used for manufacture	40 to 92
Nawaz and Tiwari, 2006	Single crystal silcon	27.23 $kgCO_2$/year	India	Coal-fired electricity generation = 0.98 $kgCO_2e/kWh$ Lifetime = 35 yrs	953
Jungbluth, 2005 in Fthenakis & Kim, 2011	Multi-crystalline silicon	Module requires 248 kWh electricity and 308 MJ natural gas	Europe	European EIs: Electricity = 0.617 $kgCO_2e/kWh$ Natural gas = 0.277 $kgCO_2e/kWh$	177
Jungbluth, 2005 in Fthenakis & Kim, 2011	Mono-crystalline silicon	Module requires 282 kWh electricity and 361 MJ natural gas	Europe	European EIs: Electricity = 0.617 $kgCO_2e/kWh$ Natural gas = 0.277 $kgCO_2e/kWh$	202

As it is expected that PV technology will mature and become less material and energy intensive with time Mann et al. (2013) has made predictions about the state of crystalline silicon PV technology in the future. Table 20 shows predicted embodied carbon values for PV modules that may be available in 2020.

Table 20: Future possible PV embodied carbon values.

Source	**Module type**	**Stated value (per m^2_{PV})**	**Location of manufacture**	**Assumptions**	**Embodied carbon value ($kgCO_2e/m^2_{PV}$)**
Mann, et al., 2014	Poly-crystalline silcon	1,500 to 2,030 $MJ_{primary}$	Europe	European primary energy factor = 0.315 European EI: Electricity = 0.617 $kgCO_2e/kWh$	81 to 110
Mann, et al., 2014	Upgraded metallurgical grade (UMG) silcon	1,330 $MJ_{primary}$	Europe	European primary energy factor = 0.315 European EI: Electricity = 0.617 $kgCO_2e/kWh$	72

While the efficiency of PV modules is expected to increase with time, it is also acknowledged that the CI of electricity grids can also be expected to reduce with time (Mann, et al., 2014). For example, the UK Government has put in place a target of an 80% cut in carbon dioxide emissions from the electricity grid by 2050, equating to a 20% cut per decade (Weight, 2011). This suggests a reduction in carbon emissions from the manufacture of PV in the future, but this situation will also reduce the carbon emissions displaced by PV-generated electricity. Where PV are produced using carbon intensive, or coal-based, electricity, but are put to use in countries which have increasingly decarbonised electricity grids, there is potential for the PV-generated electricity to have a negative impact if incorporated into a net zero carbon building where the conceptual framework relies on carbon offsetting and includes embodied carbon.

A recent, European-based study reports 0.020 $kgCO_2e/kWh$ and 0.025 $kgCO_2e/kWh$ for poly- and mono-crystalline silicon PV systems respectively (Louwen, et al., 2016); similar to the values in Fthenakis and Kim (2011). This study is based on standardised conditions, including insolation of 1,700 kWh/m^2a (as also used in Fthenakis, et al. (2008)), and assumes the local average grid electricity CI for PV production and electricity offsetting. Interestingly, the authors note that PV production has more recently shifted to China, where carbon emissions from PV production are almost twice that compared with production in Europe.

5.8. Postscript

This Chapter has discussed the concept of embodied carbon and energy. It is evident that many approaches to assessing the climate change impact of materials, products and the fabric of buildings have been attempted. In particular, the process (bottom-up, summing individual items) method, and the input-output (top-down, based on economic costs) method, for accounting for embodied energy and carbon were described. This Chapter also explains that embodied carbon and embodied energy metrics for the same product are not necessarily interchangeable, especially given that embodied carbon can be negative. Finally, the issue of embodied carbon in PV was discussed.

The next Chapter brings together the ideas and concepts discussed so far in this thesis. Zero carbon and zero energy building concepts are explored further and a new framework for examining the global problem of carbon emissions from buildings is presented.

Chapter 6. Energy or carbon? Exploring the relative size of universal zero carbon and zero energy design spaces

One aim of zero carbon, or zero energy, buildings is to help slow climate change. However, regulatory definitions frequently miss substantial emissions, for example ones associated with the materials the building is constructed from, thereby compromising this goal. Unfortunately, including such emissions might restrict the design space, reduce architectural freedom or greatly increase costs. This work presents a new framework for examining the problem. The zero carbon/energy design and regulatory space forms a sub-space of the hyper-volume enclosing all possible designs and regulatory frameworks. A new mathematical/software environment was developed which allows the size and shape of this sub-space to be investigated for the first time. Twenty-four million building design/regulatory standard combinations were modelled and assessed using a tree classification approach. It was found that a worldwide zero standard that includes embodied emissions is possible and is easier to achieve if a carbon rather than an energy metric is adopted, with the design space twice the size for a carbon metric. This result is important for the development of more encompassing regulations, and the novel methods developed applicable to other aspects of construction controlled by regulation where there is the desire to examine the impact of new regulations prior to legislation.

6.1. Preamble

The work in this chapter extends the ZeroCC ideas discussed in the context of UK dwellings to a global population of potential domestic buildings. An integrated building carbon and energy model and assessment framework developed in this research is presented. The features of the model are explained, and their importance in the creation of a universal design space, and its subsequent restriction, are explored.

A Zero Carbon Building (ZCB) is defined as a building system with calculated associated net carbon emissions that are zero or negative. The net carbon emissions are calculated as the annual operational carbon emissions from heating and electricity demand plus the annualised embodied carbon of the building envelope and the PV modules, offset against the (negative) operational carbon emissions resulting from PV electricity generation. The carbon emissions metric is normalised to the internal floor area (IFA).

A Zero Energy Building (ZEB) is defined as a building system with calculated associated net energy demand that is zero or negative. Net energy demand is calculated in the same way as net carbon emissions.

This Chapter addresses Research Question 3 and is entirely based on the paper of the same title published in Building Services Engineering Research & Technology in 2018.

6.2. Declaration of Authorship

<table>
<tr><td colspan="2">This declaration concerns the article entitled:

Energy or carbon? Exploring the relative size of universal zero carbon and zero energy design spaces</td></tr>
<tr><td>Status</td><td>Published in Building Services Engineering Research and Technology</td></tr>
<tr><td>Details</td><td>Parkin, A., Herrera, M. & Coley, D., 2018. Energy or carbon? Exploring the relative size of universal zero carbon and zero energy design spaces. Building Services Engineering Research & Technology, 0(0), pp. 1-21.</td></tr>
<tr><td>Authors' contribution</td><td>The author of this thesis has primarily (80%) contributed to developing the ideas and methodology for this paper and writing the manuscript. The Standard Building Model, used to generate the data which this paper reports, was developed entirely (100%) by the author of this thesis. M. Herrera provided advice regarding the data analysis methodology. D. Coley provided overall supervision of the work and edited the manuscript drafts. Each author's exact contribution to the paper is outlined below:

A. Parkin: Formulation of ideas (80%), Design of methodology (80%), Development of the Standard Building Model (100%), Generation/processing/analysis of data (100%), preparation of the manuscript (80%).

D. Coley and M. Herrera: Formulation of ideas (20%), Design of methodology (20%), Editing drafts of the manuscript (20%).</td></tr>
<tr><td>Statement from Candidate</td><td>This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.</td></tr>
<tr><td>Date and Signature</td><td></td></tr>
</table>

6.3. Introduction and background

There is a sense of urgency surrounding the need to reduce anthropogenic greenhouse gas emissions (IPCC, 2014; National Research Council, 1979). National and international legislation (Crown, 2008; European Parliament, Council of the European Union, 2010; United Nations, 1998) is driving the development of building standards aimed at reducing to zero, or beyond, the emissions that are attributed to the construction sector – responsible for around 20% of total global greenhouse gas emissions (IPCC, 2014). However, while there are many such standards, in almost all cases, buildings are assessed on the basis of energy not carbon (Parkin, et al., 2015). A notable exception being the recently rescinded UK zero carbon homes standard, which assessed calculated annual carbon emissions (Department for Communities and Local Government, 2010). Although carbon emissions and energy demand are linked, they are not equivalent. Carbon emissions depend on the fuel, and processes, that are used to generate the energy used in the building or embodied in its materials. For example, the carbon intensity (CI) – the carbon emission released for each unit of energy generated – of UK gas is much lower than that of UK electricity (0.216 and 0.519 $kgCO_2e/kWh$, respectively) (as of 2018, the true value is now lower; however, this is the value given in the relevant building regulations and hence pertinent to later discussions) (Department of Energy and Climate Change, 2012).

There have been recent calls for a universal, i.e. global, zero energy/carbon standard (Williams, et al., 2016), and standards such as Passivhaus are becoming global under their own momentum. This raises the question of to what degree architectural freedom and design choice would be impacted by any universal standard and whether choosing carbon, not energy, as the core metric further constrains the design choice?

6.3.1. The components of zero carbon and zero energy building standards

A review of global low and zero carbon and energy building standards can be found in Williams et al. (2016). It is interesting to note the wide range of elements that may, or may not, be included in a building standard. Aside from the choice between carbon and energy, even the types of energy demand assessed are not necessarily consistent. For example, a distinction is often made between regulated loads (heating, cooling, hot water, fans, pumps and fixed lighting) which are included in UK building standards (Department of Energy and Climate Change, 2012) and unregulated loads (anything else, e.g. plug loads – computers, televisions, washing machines, etc.) which are not. In contrast, the Passivhaus building standard is concerned with all energy demand in a building (Cotterell & Dadeby, 2012). However, rarely are embodied carbon, or embodied energy, considered – even though steel and cement alone are reported to account for 44% of UK industrial carbon emissions (Giesekam, et al., 2014). The range of approaches, and the missing of potentially important emissions, suggests various avenues for research. One clear research question being, how the range of possible buildings that could be built might be constrained by the particular choice of zero energy or carbon standard? Another, what elements within a standard are likely to be the most constraining, for example, the inclusion of embodied energy or the requirement to place all renewables within the footprint of the building? And finally, is it possible to construct a mathematical framework that would allow such issues to be studied?

6.3.2. Embodied energy and renewables provision

There are many elements to any zero energy/carbon standard, and each needs a precise definition within the standard and a statement what is and is not included. To highlight some of the many issues, we present two examples: embodied energy/carbon and renewables provision; for a list of further elements and issues, see Williams et al. (2016).

Measuring embodied carbon and energy is itself a difficult and variable activity – see De Wolf, et al. (2017) for an extensive discussion on the different methods used for assessing embodied carbon and the difficulties this presents in terms of consistency and transparency in building assessments. For some, based on the bottom-up, process method of assessment, the embodied metrics of a building are negligible when compared with its operational metrics (Dequaire, 2012; Ramesh, et al., 2010). However, use of the top-down, input–output technique for the assessment of embodied metrics leads to the opposite conclusion (Ramesh, et al., 2010; Acquaye & Duffy, 2010; Acquaye, et al., 2011; Crawford & Treloar, 2003; Dixit, et al., 2013; Stephan, et al., 2012). Furthermore, the ability of organic materials to sequester carbon adds an additional confusion. However, it is worth noting that deforestation has the effect of actively contributing to carbon emissions (Weight, 2011), so it is not necessarily safe to assume that the general use of timber products has a net beneficial impact on climate change (Hammond, et al., 2011). The use of straw as a negative embodied carbon building material is less controversial; it grows quickly and is a bi-product of food production (Sodagar, et al., 2011). As a building material, straw has a reported embodied carbon of -1.35 $kgCO_2e/kg$ (note the minus sign) (Sodagar, et al., 2011), although its embodied energy can at best be zero, but is likely to be positive due to fossil fuel based transport emissions.

One concept that is frequently applied in low and zero carbon and energy building standards is the ability of renewably generated energy to offset the energy demand of buildings (usually within an annual balance period). This allows the measured carbon emissions, or energy demand, to be reduced to zero or even made negative. There are numerous ways to generate renewable energy, but the use of photovoltaics (PV) is the most common method – in almost all cases, the PV is assumed to be mounted on the roof of the building. Given that the timing of renewable energy generation does not always match the timing of demand, this concept necessarily assumes some form of energy storage. Most building standards view the national electricity grid as a suitable place to 'store' such energy. However, for some authors, onsite self-sufficiency, usually through the use of batteries, is the ideal (Voss & Musall, 2013), presenting a particular challenge for locations with large seasonal variations in environmental conditions. It is worth noting that the embodied metrics of renewable energy generation are often overlooked and can be significant. For example, the embodied carbon value for PV modules was once estimated to be as much as 953 $kgCO_2e/m^2_{PV}$ (Nawaz & Tiwari, 2006). The general view is that embodied costs of such technology are falling, with future values predicted to be as low as 72 $kgCO_2e/m^2_{PV}$ (Mann, et al., 2014). However, it has been pointed out that global PV manufacture is tending to move from lower carbon economies in Europe to higher carbon economies in Asia (Louwen, et al., 2016).

These two examples – embodied emissions and renewables – are, as commented earlier, just two examples where the details of how they are included in a standard is likely to make a material difference to the design space. This suggests that it would be worth developing a general framework for the analysis of the potential impact of any choices.

6.3.3. Research questions

The aim of this paper is to produce a method that allows the investigation of how the different constraints imposed on the design of a building by using climate change orientated building standards reduces the size (volume) of the design space (i.e. the space containing all possible designs, e.g. variants in height, materials, form, U-values, airtightness, number of floors, window type and size), and in particular whether the size of the design space is constrained more, or less, by demanding zero carbon, rather than zero energy buildings (ZEBs). It is suggested that the new approach used of: (i) combining the building space with a large list of possible regulations into a single parametric space; (ii) modelling all combinations of buildings and regulations; (iii) analysing the results using a tree classification to discover the implications of various combinations of the regulations for various buildings has the potential for de-risking buildings codes before they are finalised and allowing some of the architectural issues of any standard to be exposed.

6.4. Methodology

The problem is set out in a completely general way and covers most relevant design and regulatory parameters (see Table 21 and Table 22). The idea is not to discover if a particular building is zero carbon (or energy), but to discover how the design space contracts and design limits arise as the regulatory framework becomes more aggressive. A parametric approach is taken, but uniquely, the regulatory space is also parameterised.

6.4.1. The design and regulatory spaces

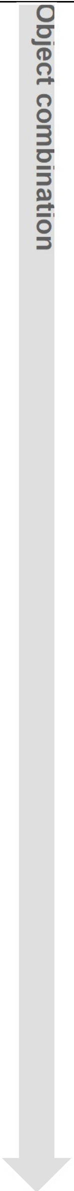
In general, the building design space, **S**, consists of a large number of dimensions made from a mix of real, integer and Boolean variables, for example, building dimensions (real), number of storeys (integer) and the inclusion or not of active cooling (Boolean). A subset, **S'** of **S**, will be highly relevant to the energy use of a building or its carbon emissions and implicated in the regulations. The regulatory energy or carbon accountancy space, **R**, consists of a list of Boolean dimensions, for example, include (or not) embodied energy, allow (or not) remote generation from renewables and include (or not) non-regulatory electricity use. In addition, there is a space, **L**, specifying all possible locations any building might be sited. **L** also contains a description of the energy supply metrics of the location, for example the CI of the electricity grid. The list of variables considered was taken from (Williams, et al., 2016) and is detailed in Table 21 and Table 22.

In order to make the problem tractable, we limit the range of each variable in **S'**. The range of each variable has been chosen to be realistic and cover the full range of likely values (see Table 22). For example, both a low embodied carbon construction based on straw and a high embodied carbon one using brick are included, thereby covering both extremes. (Although other options like low embodied energy recycled brick exist, it is the extremes we need to identify.) The footprint of the building is allowed to range from 45 to 450m^2 in steps of 45m^2, giving 10 possible values for this dimension – it would be trivial to change these limits to study larger buildings. This gives a discretised space, **S''** with members s''. **L** is similarly limited, in this case to six locations, to give **L'**, again, other locations could be chosen.

S'', **L'** and **R** are combined into a single space, **Z**. A member (or case), z, of **Z** then identifies a single theoretical building examined under a single regulatory framework in a single location. With the combination of parameters studied, **Z** has 24 million members. The energy use (with generation from renewables considered negative) or carbon emissions (with the potential for some materials to sequestrate carbon) for each z of the 24 million in **Z** are then found by the use of a suitable energy/carbon model. Some members of **Z** will be found to be carbon or energy neutral or better. We term this subset $\mathbf{Z_z}$. A classification tree analysis can then be used to compare and contrast members of $\mathbf{Z_z}$ with the whole of **Z** or with members of **Z** which are not members $\mathbf{Z_z}$. Thereby answering questions such as, do most members of $\mathbf{Z_z}$ have fewer than 10 storeys? And, do most buildings require offsite renewables generation to be classified as zero energy? It is important to realise that the buildings studied are either ϵ of $\mathbf{Z_z}$ or not; i.e. the solution space is binary and no account is taken of how close to passing or failing the zero energy/carbon regulation a solution is. This mimics the real life situation, where a building must simply pass the regulation.

A new Standard Building Model (SBM) was developed in Matlab to simulate the construction and performance of multiple buildings in multiple global locations. Virtual materials objects, with embodied carbon and energy, and where applicable thermal resistance properties were combined by SBM to create virtual building objects (see Table 21). These were then assessed under defined conditions (locations, number of occupants, infiltration levels, etc.) to generate SBM cases (i.e. members of **Z**). The properties of the building objects and the specifications of the assessment conditions were varied, as detailed in Table 22. The overall result was the generation of 24.7 million SBM cases, filling the space **Z** and enclosing all the possible combinations of building design and assessment conditions simulated by SBM. In this work, only domestic buildings are considered, although this could easily be expanded to the different occupancy densities and loads found in commercial building.

Table 21: SBM virtual objects (which forms the list of all parameters considered).



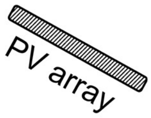
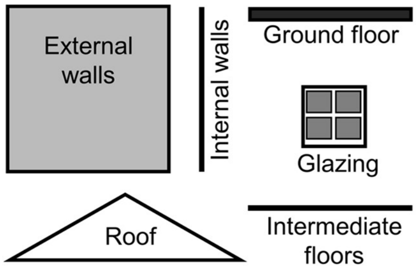
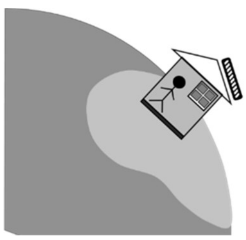
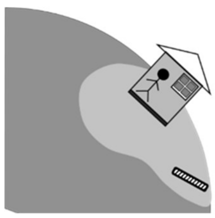
Standard Building Model Virtual Objects		Virtual Object properties
Renewables Objects  PV dimensions determined by *Building Object* dimensions	**Materials Objects** 	Embodied carbon ($kgCO_2e$ per m^2) Embodied energy (kWh per m^2) Thermal resistance (m^2K/W) - only if external envelope component
	Materials Objects combine to create:	
	Building Objects 	Dimensions (footprint, height, etc.)
Building Objects and *Renewables Objects* combine with locations to create:		
Building System Objects  (PV onsite)  (PV remotely sited in Accra)		Assessment conditions (no. occupants, infiltration levels) Environmental conditions (temperature, insolation, energy grid)
Building System Objects are assessed using a methodology that has a defined Balance period (*Annual* or *Monthly*) Boundary condition (*Operational* metrics only, or *Operational* + *Embodied* metrics included)		
Each assessment outcome is one CASE		

Table 22: Building object properties and assessment conditions (i.e. the range of parameters considered).

<table>
<tr><th></th><th>Variable</th><th colspan="6">Value range / Categories</th></tr>
<tr><td rowspan="9">Building Design</td><td rowspan="2">Principal construction material</td><td colspan="6">Brick</td></tr>
<tr><td colspan="6">Straw (assuming no carbon sequestration)
Straw (assuming carbon sequestration)</td></tr>
<tr><td>Footprint (m²)</td><td colspan="6">45 – 450 m² in steps of 45 m²</td></tr>
<tr><td>Width (m)</td><td colspan="6" rowspan="2">Limitations were placed on the aspect ratios permitted (to avoid modelling unreasonably narrow and/or tall buildings).
Valid building widths were calculated using aspect ratios 1, 0.5, 0.25 and 0.125 and
$$Building\ width = \sqrt{aspect\ ratio \times building\ footprint}$$
The modelled buildings have different wall depths, so an additional requirement was included that the internal floor area for one storey must be greater than 25 m².
1, 2, 4, 8, 16 and 32 storeys were modelled, with the same limitation on aspect ratios.</td></tr>
<tr><td>Height (storeys)</td></tr>
<tr><td rowspan="3">External wall U-values (W/m²K)</td><td colspan="2">U-values (W/m²K)</td><td>0.18</td><td>0.15</td><td>0.12</td><td>0.10</td></tr>
<tr><td rowspan="2">Insulation depth (mm)</td><td>In Brick buildings</td><td>110</td><td>130</td><td>180</td><td>220</td></tr>
<tr><td>In Straw buildings</td><td>380</td><td>475</td><td>600</td><td>700</td></tr>
<tr><td>Glazing area</td><td colspan="6">10, 20, 40 and 80 % of the external walls</td></tr>
<tr><td rowspan="3">PV Specification</td><td rowspan="3">PV specification
(monocrystalline silicon)</td><td colspan="2"></td><td colspan="2">Embodied carbon ($kgCO_2e/m^2_{PV}$)</td><td colspan="2">Embodied energy (kWh/m^2_{PV})</td></tr>
<tr><td colspan="2">Low embodied metrics[1]</td><td colspan="2">149</td><td colspan="2">241</td></tr>
<tr><td colspan="2">High embodied metrics[2]</td><td colspan="2">953</td><td colspan="2">318</td></tr>
<tr><td rowspan="7">Assessment Conditions</td><td>Occupant density</td><td colspan="6">No occupants; 35 m²/person; 20 m²/person</td></tr>
<tr><td rowspan="3">Glazing U-value (W/m²K)

Regardless of U-value, embodied metrics for glazing do not change.</td><td>1.4</td><td colspan="5">Complies with UK Building Regulations 2014[3]</td></tr>
<tr><td>0.8</td><td colspan="5">Passivhaus compliant[4]</td></tr>
<tr><td>0.68</td><td colspan="5">Based on the ULTRA range[5]</td></tr>
<tr><td>Air infiltration</td><td colspan="6">0.042 + MVHR; 0.700; 0.343 air changes at normal pressure</td></tr>
<tr><td>Calculation boundary</td><td colspan="6">Operational only
Operational + Embodied</td></tr>
<tr><td>Balance period</td><td colspan="6">Annual; Monthly</td></tr>
</table>

	Building location	Athens; Carcassonne; Macapa; Mumbai; Oslo; Seattle
	PV location	Onsite; Sited remotely in Accra – always orientated for optimum PV generation

1 (Mann, et al., 2014)

2 (Nawaz & Tiwari, 2006)

3 (HM Government, 2013)

4 (Cotterell & Dadeby, 2012)

5 (Green Building Store, 2017)

Table 23: Location, temperatures and electricity grid CIs (ordered by latitude).

City	Latitude (°N)	Country	Mean annual insolation (kWh/ $m^2_{horizonatal}$)	Mean annual temperature (°C)	National electricity grid CI ($kgCO_2e/kWh$)[1]
Macapa	0.04	Brazil	1,700	26	0.087
Mumbai	19	India	2,100	27	1.003
Athens	38	Greece	1,600	19	0.876
Carcassonne	43	France	1,300	13	0.078
Seattle	48	USA	1,200	9	0.610
Oslo	60	Norway	1,000	5	0.003

1 (IPCC Technology and Economic Assessment Panel, 2005)

The performance of each case was assessed in terms of both net carbon emissions and net energy demand (normalised to the internal floor area). A zero carbon building (ZCB) is defined as a case assessed to have net zero, or negative, carbon emissions. Similarly, a ZEB is defined as a case assessed to have a net zero, or negative, energy demand.

PV generated electricity is the offsetting mechanism relied on to reach the zero carbon or energy goal, and each SBM case can be classified as a ZCB, a ZEB, both or neither. Other possible building-mounted renewables for electricity generation have been ignored, as has facade-mounted PV. This is because such technologies (such as roof-mounted wind) have failed to find traction and their output highly dependent on the precise urban environment – which at this level of assessment is unknown.

6.4.2. The standard building model

The SBM is an hourly heat loss/gain model which ignores the temporal impact of thermal mass (as this would require a dynamic model) and solar gains (as this would require detailed information about window location and the form of the external landscape). The assumption is that, as this work is discussing zero carbon or energy design, attempts will have been made to shade any glazing appropriately – this is unlikely to be the case for all buildings, but represents the kind of wording of desire likely to be found in an environmental building standard. The building footprint is determined by the external dimensions, whereas the internal floor area takes into account the external wall thickness. The SBM makes hourly estimates of the heat loss or gains through opaque and transparent elements by calculating the area-weighted mean U-value (i.e. the model is geometry free), with the temperature difference being given by the set-point and the hourly weather file (see below). Floor losses are ignored. Electrical gains and other parameters of the model are as given in the text below and in Table 21, Table 22 and Table 23. Occupancy density (for the estimate of metabolic gains) was set to 20–35m^2/person, biasing the work away from more wealthy occupants (35m^2/person being the Passivhaus Certification assumption). Each hour the gains are compared to the losses (including ventilation), and energy is used to meet the set points. Several of the assumptions in the model are unlikely to be valid in all countries, and others represent simplification of the situation, for example, the wide scale adoption of PV would lead to energy and carbon economies of scale; domestic electrical use would be a function of location and wealth. In short, we have tried not to model the buildings exactly, but how they might be considered within a domestic building code, where assumptions of occupancy densities, incidental gains, emission factors, the embodied energy of key materials, set-points, etc., are likely to be specified in the code and not building dependent. Other issues such as the pollution caused by the manufacturing of PV and other components and waste disposal at end of life have been ignored, as these are rarely found in building regulations. The SBM was validated against the Passivhaus standard and pre-existing work on embodied emissions from buildings (see Appendix 1).

The SBM has been designed to give an hourly estimate of energy use of the building for comparison with any renewables generation and then to sum over the accountancy period given by the regulation space **R**. The use of a dynamic simulation might alter the hourly estimates, but is likely to have little impact for the summed values and hence on the results. It is based on PHPP, the model used to develop all certified Passivhaus, and hence the physics is well tested on over 40,000 buildings and for a similar purpose: the comparison of energy consumption against a low energy standard.

6.4.3. Building location

Six locations (**L'**) were chosen to allow for the simulation of a range of external temperatures, insolation levels and electricity grid CIs – from fossil fuel to renewables based societies. Table 23 shows the relevant characteristics of the different locations. Hourly external temperature data and insolation levels for the different locations are based on data from NASA (NASA, 2015).

6.4.4. PV location

All buildings were modelled for two scenarios. The first assumes that the PV array is roof mounted on the building. Under this assumption, the carbon offset value of PV generated electricity is negative, but of the same magnitude as the local electricity grid CI (as in Table 23). Buildings are modelled with a PV array sized to cover the entire roof (to give the maximum potential for the building to be zero energy/ carbon), angled for optimum annual electricity generation (in practice, however, there might be a minimum angle to avoid the accumulation of dirt). The size of the PV array depends on the shape of the building and determines the amount of electricity generated and the total embodied carbon and energy for PV.

The second scenario allows for offsetting via a remote renewable source located in a more favourable location. This represents the situation where a building standard allows remote offsetting or where national grids have been interconnected. Accra was chosen as the location for the remotely sited PV; given its low latitude (5.6°N), daily PV generation is relatively consistent across the year. This means that short-term (daily) storage of electricity in batteries is possible, thereby removing the need for such electricity to be 'stored' in the local electricity grid. In these circumstances, PV generation can satisfy electricity demand throughout the year without the need for support from traditional energy infrastructure. Under this assumption, the carbon offset value of PV generated electricity is negative, but of the same value as the electricity grid CI in Accra (see Table 24). A further negative CI element is added to the carbon offset value of the PV generated electricity to reflect the removal of the need to build traditional energy infrastructure. For example, the CI associated with just the construction of a 1GW nuclear power station has been calculated to be 0.0014 kgCO_2e/kWh (MacKay, 2009). Embodied metrics associated with the necessary onsite batteries are included in the overall building embodied metrics (see Table 24).

6.4.5. Electricity demand

SBM assumes that electricity demand is largely tied to occupancy levels. Demand rises and falls throughout the day, with a constant base load included to account for appliances on standby mode or running continuously (e.g. fridges). The electricity demand profile is based on the patterns of demand identified in Knight, et al. (2007) and varies hourly across the day, the week and the year. The overall electricity demand level is based on the usage of a typical UK family of four (Energy Savings Trust, 2012), with a value of 1,350 kWh/a/person. The use of UK-based data here and at several points below does not impact on the global validity of the conclusions reached. The reason for using UK values is the desire to fix these variables in order to draw out the impact of the building-centric variables under study, and because the data are not sufficiently accurately known for the other locations.

Table 24: Assumptions when the PV array is remotely located in Accra.

SBM Assumption	Notes
Accra electricity grid CI: 0.705 kgCO$_2$e/kWh	Assuming the Africa average[1]
Electricity CI associated with traditional power station construction: 0.0014 kgCO$_2$e/kWh	Based on[2]
Carbon offset value of remote PV generated electricity in Accra: -0.7064 kgCO$_2$e/kWh	= -(0.705 + 0.0014)
Electricity demand CI based on the electricity grid local to the building	See national electricity grid CI values in Table 3
Battery storage: NiMH	Assumed lifetime: 15 years
Battery embodied carbon: 283 kgCO$_2$e/occupant (over 15 years)	Based on[3]
Battery embodied energy: 458 kWh/occupant (over 15 years)	Based on the battery embodied carbon above and European electricity CI[4] = 0.617 kgCO$_2$e/kWh

1 (IPCC Technology and Economic Assessment Panel, 2005)

2 (MacKay, 2009)

3 (McManus, 2011) and (Brook & Bradshaw, 2014)

4 (Voss & Musall, 2013)

6.4.6. Heating and cooling

Heating is used to raise the internal temperature to the heating set point (18°C when occupied, 13°C when unoccupied – based on Public Health England data (Public Health England, 2014) and BS EN 15251, 2007), and is reduced by hourly metabolic heat gains, and those from electrical equipment when present. Domestic hot water is not accounted for in the SBM energy demand calculations, and gains from domestic hot water use are not included either. The heating fuel is assumed to be gas (with the UK gas CI of 0.216 kgCO$_2$e/kWh) or electricity from the local grid, depending on which source has the lower CI.

Cooling is used to reduce the internal temperature to the cooling set point (25°C when occupied, 30°C when unoccupied – based on Cotterell and Dadeby (2012) and BS EN 15251. It is assumed that all windows can be opened, allowing the internal and external temperatures to reach equilibrium, when possible. This means that no cooling is active when the external temperature is below the cooling set point. It is also assumed that the windows will be closed when the cooling system is active. The cooling system in SBM has a coefficient of performance of 0.5814, based on Szokolay (2008) and is powered by electricity from the local grid (e.g. CI as in Table 23).

These set points are unlikely to be truly representative of all locations in the study, and many buildings would be operating within an adaptive comfort framework. They have been used to ensure uniformity, to avoid confounding factors and due to a lack of consistent data for some locations.

6.4.7. Air infiltration

The buildings were modelled with three levels of air infiltration (Table 25). The heating system present in the SBM buildings depends on the levels of air infiltration. A traditional heating system is present when air infiltration levels are high, but is replaced by a mechanical ventilation with heat recovery (MVHR) unit when air infiltration is low, thereby mimicking the use of MVHR in air tight buildings such as those conforming to the Passivhaus standard.

Table 25: SBM infiltration levels.

Infiltration level (air changes per hour at normal pressure)	**Notes** **Given by *infiltration at typical pressures* = 0.07 x *infiltration at* 50 Pa**
0.042	Equivalent to 0.6 air changes at 50 Pa, i.e. the maximum uncontrolled infiltration level for Passivhaus compliance[1]. MVHR system (with an efficiency of 90 %) is included in embodied metric calculations to supply the fresh air needed for good air quality, as required in the Passivhaus building standard.
0.343	The uncontrolled infiltration required for Passivhaus good air quality compliance, based on 30 m^3/person per hour, and the Passivhaus default occupancy of 35 m^2/person[1]. Traditional heating system included in embodied metric calculations instead of the MVHR system.
0.700	Equivalent to 10 air changes at 50 Pa. The approximate infiltration level for UK Building Regulations compliance[1]. Traditional heating system included in embodied metric calculations.

1 (Cotterell & Dadeby, 2012)

6.4.8. Principal construction materials

The principal construction materials used in the buildings were either *brick* (brick, block and concrete with foam-based insulation) to represent a high carbon construction, or *straw* (timber with straw insulation), to represent a low carbon construction. Other possible cases, not modelled in this work, can be seen as intermediate to these extremes. The high carbon construction details are based on Charlett and Maybery-Thomas (2013). The low carbon construction details are based on Pelly & Mander (2014). In all cases, the ground floor consists of a solid concrete floor (as in Charlett and Maybery-Thomas). Internal walls for all buildings are based on the cross-laminated timber walls in Pelly and Mander, 2014 to maximise the potential for carbon sequestration.

Straw buildings are assessed under two assumptions: carbon sequestration is applicable to timber and straw building components (i.e. embodied carbon for such elements is negative – this is a controversial position, but again, represents the extreme); or carbon sequestration is not applicable at all (i.e. embodied carbon for such elements is positive or zero).

6.4.9. Calculation boundary

Two accountancy boundaries were applied to the assessment of the buildings. *Operational* includes only the carbon emissions, or energy demand, associated with the operation of the buildings (e.g. heating and electricity demand); *Operational + Embodied* also includes the carbon emissions, or energy, used to create (or stored in, in the case of sequestration) the fabric of the building.

All embodied energy data and operational energy values (demand and generation) are measured in terms of final energy, not primary energy. This makes the distinction between energy and carbon emissions more obvious and removes the possibility of the choice of heating/cooling fuel being more important than issues such as building fabric or architecture. The reported carbon emissions however are based on primary energy use. The embodied energy values for all materials and products were obtained from the literature and based on the bottom-up process method of assessment. By converting embodied primary energy values to final energy (via the mean European electrical primary energy factor), the role of the national energy mix of the manufacturing location is removed, thereby accounting for the potential to obtain materials from various locations. In a global study, such as this, it is impossible to guarantee where materials might be sourced over coming decades. However, this does mean that materials that always use different primary mixes in their manufacture (such as steel and aluminium) are less differentiated than a primary energy-based accountancy would suggest. Once better, worldwide, data on embodied emissions exist, and primary energy accountancy could be used instead.

CIs (or carbon emission factors) are applied to site energy demand and generation following the method used in the UK Standard Assessment Procedure (Department of Energy and Climate Change, 2012). These give a direct indication of the carbon emissions associated with the site energy balance. Using the same assumptions as in the energy scenario described above, embodied carbon values are also sourced from the literature (via the ICE database (Hammond, et al., 2011)). The manufacturing assumptions applied in the literature (which are often dependent on the method and location of production) are similarly applied in this work; the location of the modelled building does not alter its embodied carbon characteristics (an assumption required by the lack of data for most countries).

In this work, the building life is assumed to be 60 years, and the PV array and glazing are assumed to have lifetime of 30 years – i.e. these buildings need two PV arrays over their lifetime. Redecoration and maintenance are not included. This is a simplification, justified by the difficulty for accounting for redecoration in any building regulations. However, studies such as (Rauf & Crawford, 2013) indicate that they could be significant.

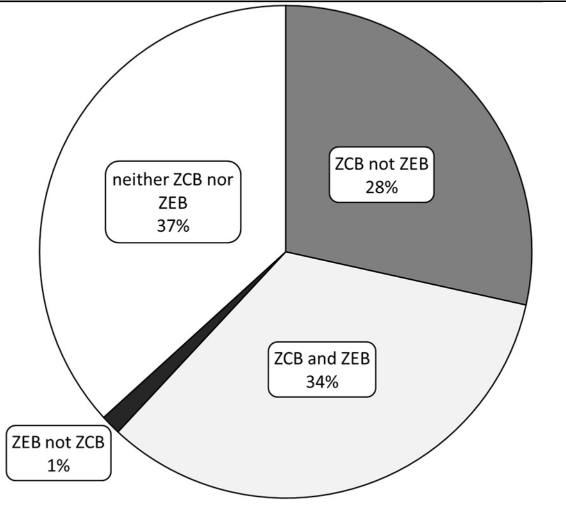
6.4.10. Balance period

Two different balance periods were applied to the assessment of the PV generation/energy demand balance. In the *Annual* scenario, excess PV generation occurring at one time in the annual cycle (e.g. in summer) is used to offset demand at another point in the cycle (e.g. in winter). In the *Monthly* scenario, excess PV generation must be used within the monthly cycle. For calculation purposes, any surplus left at the end of the month is lost, meaning that summer generation cannot be used to offset winter demand.

6.5. Results

All possible combinations of the above construction and accountancy parameters were analysed by the SBM. Of the 24.7 million cases, 37% were found to be neither ZEB nor ZCB (Table 26). Sixty-two percent were found to be ZCB, whereas only 35% ZEB. This is the first indication that building standards based on carbon not energy might be more universal and less constraining of the design space. In addition, while a zero energy classification is almost always associated with a zero carbon classification, only around half the total number of ZCBs are simultaneously ZEBs.

Table 26: Classification of cases.



ZCB not ZEB	Case classified as zero carbon, but not zero energy
ZCB and ZEB	Case classified as both zero carbon and zero energy
ZEB not ZCB	Case classified as zero energy, but not zero carbon
neither ZCB nor ZEB	Case not classified as zero carbon or zero energy

The whole population of cases was analysed using a classification tree algorithm. The classification tree uses recursive partitioning to split the data into ever smaller subsets of similar classes. Beginning at the root node, the algorithm selects the feature (the input variable in Table 22) that is most predictive of the target class (ZCB or ZEB). The population is then split into subsets based on the feature values (the value range or category in Table 22). The algorithm continues to further split the nodes, based on the most predictive feature at that node, until a stopping criterion is reached. This occurs at a node if:

- all of the cases fall into the same class; a pure node;
- there are no remaining features to distinguish among cases;
- the minimum leaf node size is reached (500,000 cases or 2% of the total population).

The feature that is most predictive of the zero carbon target (i.e. forms the greatest constraint) is the location of the building (see Figure 30). The first classification tree split divides the SBM population into those in locations with high electricity grid CIs and those with low electricity grid CIs. ZCBs and ZEBs were found in all locations (see Figure 33). Meaning that at least in theory, it is possible to build zero carbon or ZEBs in all the locations studied. However, from the energy perspective, the feature that is most predictive of the zero energy target (again, that which forms the greatest constraint) is the number of storeys (see Figure 31). This is unsurprising (and is in line with the findings in Heinonen & Junnila (2014) and Stephan, et al., 2013b as the taller the building the greater the difficulty of the PV providing all the energy required. However, ZCBs were possible for all building heights, and ZEBs were possible in the cases of all but the tallest buildings (see Figure 32).

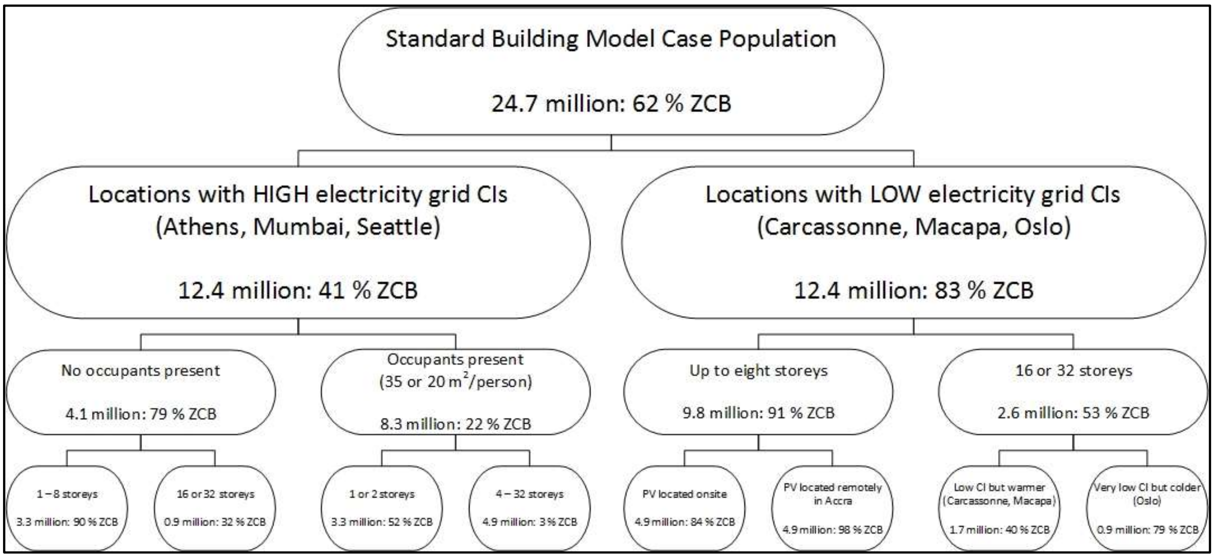


Figure 30: Trimmed carbon classification tree showing the top four node levels.

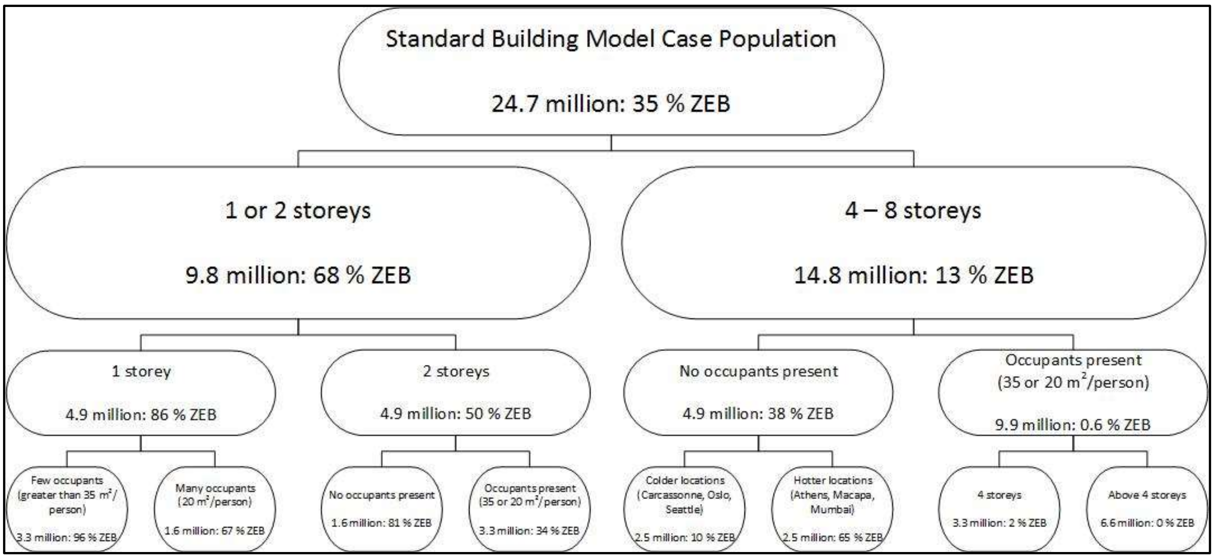


Figure 31: Trimmed energy classification tree showing the top four node levels.

Both the carbon and energy classification trees contain more node levels than shown in Figure 30 and Figure 31, which identify further, sometimes repeated, splitting features. All features identified were also scored and ranked according to their prominence rather than location in the classification trees using Equation 2. Table 27 shows the ranking of features as identified in the carbon classification tree. The highest scoring feature is ranked first.

Equation 2

$$Feature\ score = \sum_{\substack{Node \\ levels}} \frac{Number\ of\ times\ feature\ appears\ in\ tree}{Node\ level\ at\ which\ feature\ appears}$$

It should be noted that ranking the energy classification tree features using Equation 2 reveals the same top four features, in the same order, as is the case for the carbon classification tree. The difference is that, in the case of energy, no further features are identified.

Table 27: Ranked carbon classification tree splitting features.

Feature ranking	Feature
1	Building height
2	Location
3	Occupants
4	Balance
5	Boundary
6	PV location
7	Glazing %

As well as the features identified as being important, it is worth noting the variables that have not been identified by the classification trees as splitting features at the level of detail shown in the trees. These are construction material (brick or straw), infiltration level, PV specification, glazing U-value, external wall U-value, building width and building footprint.

The location of the building is the feature ranked second in Table 27 as a predictor of reaching the zero target (i.e. it is the second most powerful constraint). However, rather than the location's climate being dominant, Figure 33 shows that the lower the location's electricity grid CI, the more likely it is that cases will be classed as ZCBs. It is also evident that the higher the electricity grid CI, the more likely it is that cases classed as zero carbon are also classed as zero energy and vice versa.

Figure 34 shows how the proportions of ZCBs and ZEBs fall at similar rates as the number of occupants increases.

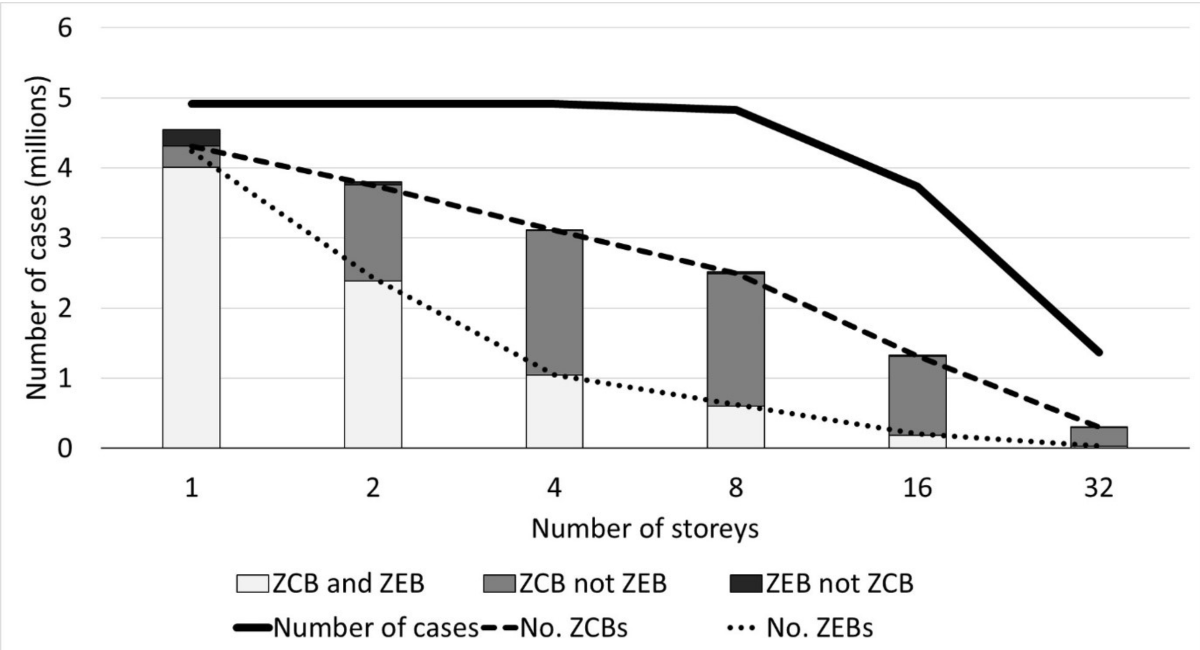


Figure 32: Change in ZCB and ZEB proportions with building height. As a result of the aspect ratio restrictions, discussed in Table 22, the number of cases is 4.9 to 1.4 million depending on the number of storeys.

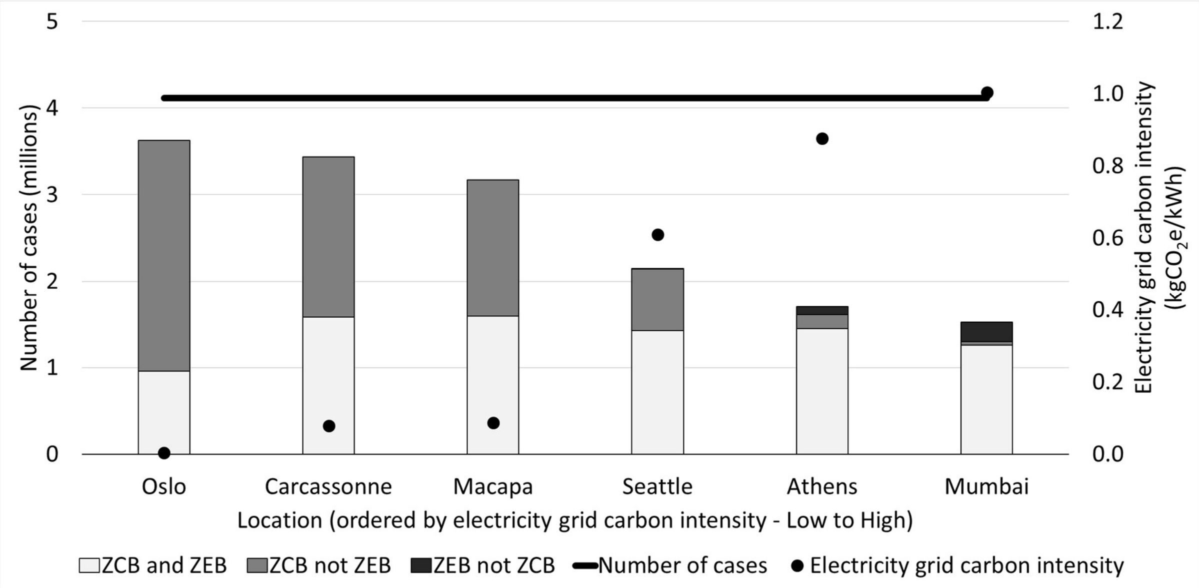


Figure 33: ZCB and ZEB proportions for different locations. The number of cases is 4.1 million for each location.

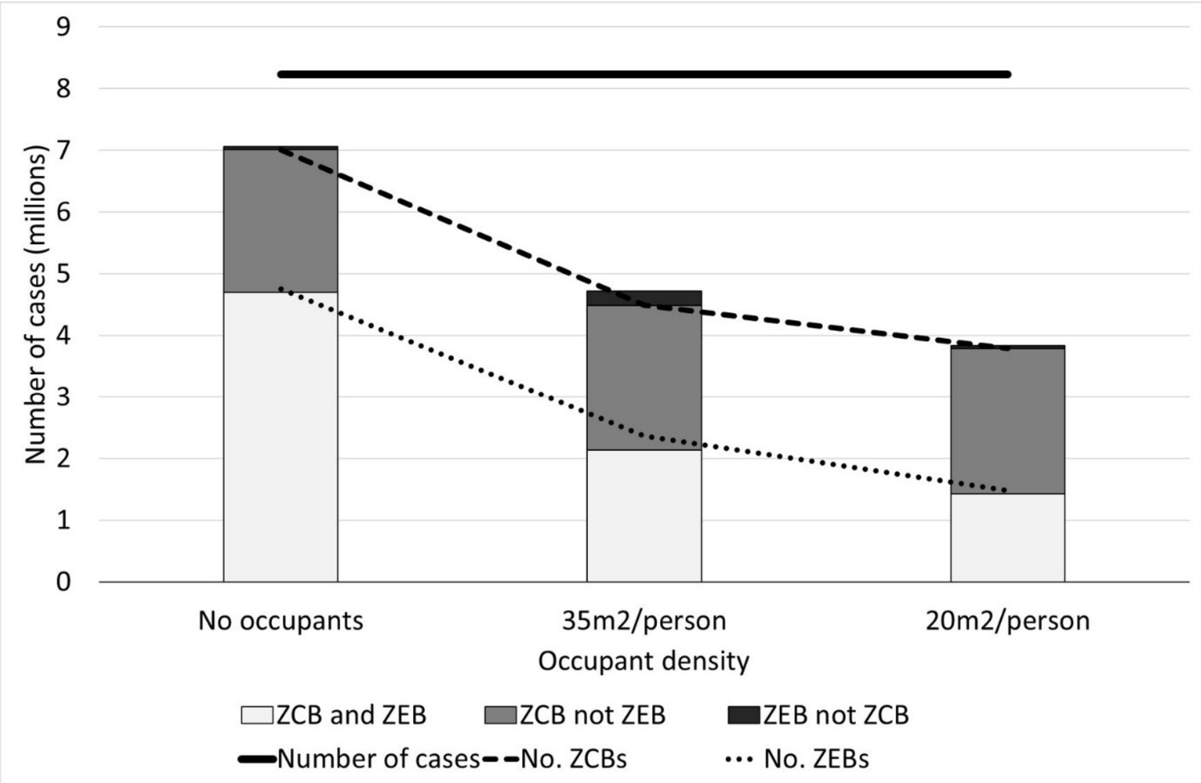


Figure 34: ZCB and ZEB proportions for different occupancy levels. The number of cases is 8.2 million in each scenario.

6.6. Discussion

The results highlight three particularly prominent features that play a role in achieving a zero carbon, or energy, building in SBM: height, location and occupancy density. These three features are strongly linked to electricity demand and PV generation and the subsequent balance of carbon emissions and carbon offset. This list will be surprising to those that might have expected items such as U-value or construction material to be the key drivers. The exact nature of these results will be dependent on assumptions used in the modelling, and it would be wrong to draw too much attention to the values obtained. However, it is clear that the approach works and generates a rich vein of data for analysis using classification trees.

Location is important in both the carbon and the energy classification trees, but for different reasons. Insolation levels are strongly linked to location; lower latitudes tend to be associated with warmer, and sunnier, conditions. For this reason, it is easier to achieve a ZEB where the climate is warm but not hot and there is abundant sunshine (an unsurprising result), e.g. see the example building shown in Figure 35. In the carbon classification tree, location is the most important splitting feature. However, the split is on the basis of the electricity grid CI, not temperature or insolation as might be expected (a less expected result).

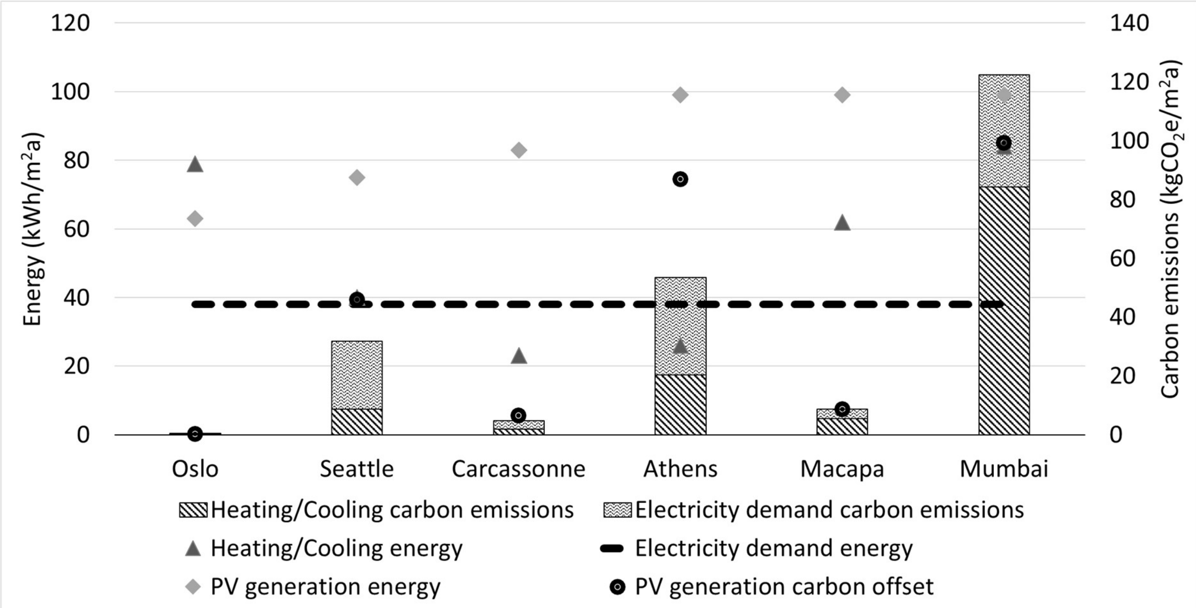


Figure 35: Heating/cooling energy demand, PV generation and associated carbon emissions (or offset) for the same typical house-sized building (2 x storeys) in different locations. PV located onsite. Locations ordered by temperature, coldest (left) to hottest (right).

In the scenario where the PV arrays are remotely located in Accra, both the magnitude of PV generation, and the ratio of carbon emissions from electricity demand to the carbon offset from PV generated electricity, are important. For example, the Accra to Oslo electricity grid CI ratio is 1:235, so each kilowatt hour of electricity generated in Accra offsets the carbon emissions from 235kWh of electricity demanded in Oslo. In addition, it is possible to generate far more PV electricity in Accra per unit area of PV array than in Oslo.

The PV location feature raises the issue of the philosophy of zero. While it is not yet practical to transfer PV generated electricity across the globe, the benefits of displacing emissions from carbon intensive electricity grids are globally relevant, regardless of the location of the displacement. A zero carbon philosophy is better placed, than a zero energy equivalent, to take advantage of an opportunity to remotely locate PV arrays. In addition, such a scenario would place no limitation on the zero building design space from the perspective of building location or building size.

6.6.1. Features appearing at deep node levels in the classification trees

The balance period and assessment boundary features only appear at the deeper node levels in the classification trees. In addition, most features relating to the thermal envelope properties do not appear in the trees at all at the level of detail in the classification trees in this work. These results have profound meaning for where focus needs to lie when designing environmental building codes.

It is also interesting to note that at no time is the population of cases split on the difference between PV with a high embodied carbon value and that with a low embodied value or between brick and straw buildings (even where carbon sequestration is included in the assessment). This indicates that, under the analysis presented here, the significance of embodied metrics alone is outweighed by the overall issue of energy demand and PV generation (e.g. see Figure 36). This however might not be true if the embodied data was assembled using different boundaries.

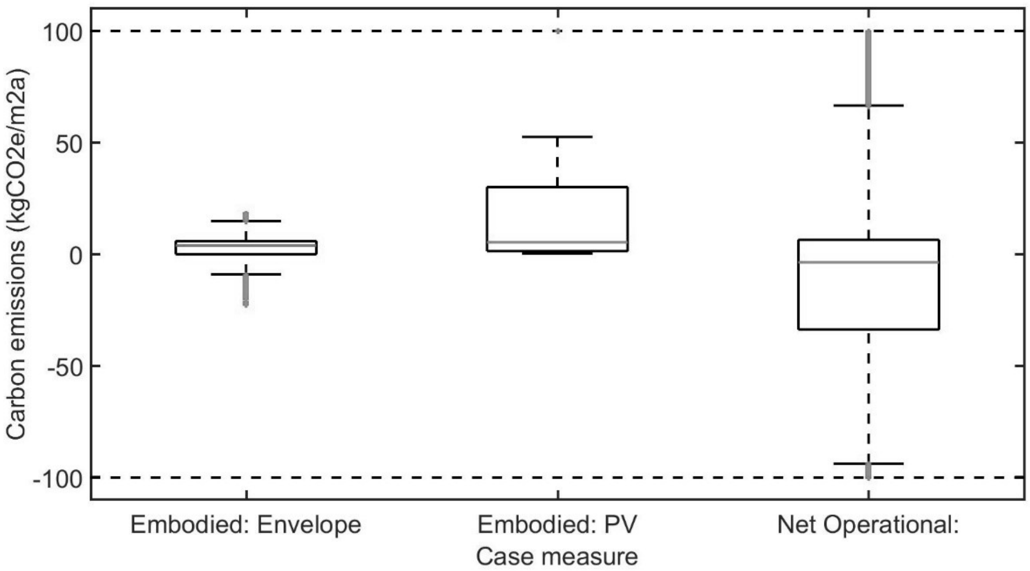


Figure 36: Boxplots showing the range of values associated with different aspects of the net carbon emissions for each case. Boxes show the interquartile range (IQR). Maximum whisker length extends to 1.5 IQR of the upper and lower quartiles. Beyond the ends of the whiskers outliers are plotted individually.

These results raise some interesting philosophical questions. The central one being: what should be included or not included in any practical standard? Should a standard be focused on the key issue – climate change – or on a proxy – energy use? It is interesting to note that Passivhaus has stuck firmly to a fabric-first, energy-based, no embodied emissions, standard. However, if we decarbonise the energy supply to buildings by the use of building mounted renewables faster than we decarbonise manufacture (including over-seas manufacture) of building components building, embodied carbon would become more important.

It is worth noting that there is enthusiasm from some quarters for a more carbon, possibly whole life, approach as evidenced by publications from RICS (2018) and BS EN 15804:2012 + A1:2013 and BS EN 15978. It is also worth noting that others have anecdotally suggested that carbon compliance might be easier than energy compliance (e.g. by the use of biomass boilers in energy inefficient buildings); however, here, we present a systematic analysis of the situation over large search space to look at the general situation.

The work has various limitations. The use of a heat-balance energy method, rather than a dynamic simulation, might be seen as an over simplification. However, this is the method used for Certified Passivhaus design, in part because it needs less detail about the building. This makes it ideal when looking broad questions, rather than specific buildings. The model in its current form ignores solar gain. This is in part because such gains depend highly on architectural details. However, the approach could be extended to make such gains a parameter of the search space, and it would be interesting to see the impact of this on the results. Dynamic elements, such as thermal mass, could be included in a similar way. We have limited the renewables to PV. This due to its growing adoption, that it is easy to complete calculations of energy production for any location and because embodied carbon values have been published. However, there are other technologies, such as ground source heat pumps and biomass boilers that could be studied in further work, and it is unknown to what degree this makes some of the findings less general.

6.7. Conclusion

In this work, 24.7 million building specification-assessment rule combinations were generated to simulate the global construction of many different types of building complying with a variety of possible zero carbon, and energy, building standards.

It was found that a ZCB standard, because it focuses on carbon emissions, allows for a more varied design space. Several assumptions were made in the work, and it would be interesting to see how changing these, for example including solar gains, a more diverse range of occupancy densities, a more complex electrical gains timetable or including redecoration might change the some aspects of the message – if such data could be found. It would also be worth considering how a sensitivity analysis might be completed; or looking at the impact that the assumed boundaries of the study might have, after all, architecture is almost unbounded in its possibilities. The use of novel materials, or how the size of the space changes for extreme designs such as very tall, but slender buildings, would be worth studying. However, the value in this work lies not in the accuracy of heat loss estimations or the embodied energy of particular buildings, but in the idea of the value of calculating how the volume of the design space changes and is constricted under the influence of the building regulations that might be in place.

This work demonstrates that, on a global level, the design space is approximately 1.8 times greater if achieving zero carbon is the focus of building codes rather than zero energy, and also clearly demonstrates that, at a fundamental level, the use of carbon rather than energy opens up more opportunities than it eliminates. Hence governments are recommended to consider swapping the current energy focused approach to a carbon focused one (after due consideration is given to other complicating factors such as the method of implementation). Not only does the focus on zero energy reduce the design space by almost half in comparison with zero carbon (see Table 26), but a focus on carbon would also be in line with the reason for wanting zero energy/carbon buildings: reducing carbon emissions to protect humankind from climate change. In addition, the novel methods developed are applicable to many other aspects of construction controlled by regulation where there is the desire to examine the impact of new regulations prior to legislation.

6.8. Acknowledgements

This work is supported by the Engineering and Physical Sciences Research Council under Grant 1355192.

6.9. Appendix I. Validation

To test the validity of the SBM requires both the energy demand and the embodied algorithms to be considered separately. For the energy demand, a house was modelled replicating as closely as possible the specifications recommended for a PH standard building and a building that complies with UK building regulations. The SBM calculated annual heat energy demand was then compared with that defined by two building standards (see Table 28). In both cases, the SBM output is higher than the estimate, or requirement, for the two comparison standards. However, SBM does not account for solar gains, which are estimated to be around 11 kWh/m^{2}a (Cotterell & Dadeby, 2012). In addition, SBM does not account for gains from the domestic hot water system, which are estimated to be between 5.8 and 14.4 kWh/m^{2}a for a Passivhaus standard construction, but may be as much as 18.6 kWh/m^{2}a for a typical UK house (Cotterell & Dadeby, 2012). When these other sources of heat gains are included, the SBM output reflects the standard requirements, indicating that the energy algorithm is valid.

Table 28: Comparison of SBM output with UK Building Regulations and the Passivhaus standard for a building located in Watford, UK.

SBM component	**Based on UK building regulations** (Department of Energy and Climate Change, 2012)		**Based on the Passivhaus standard** (Cotterell & Dadeby, 2012)	
	Reference values	**SBM input**	**PH standard requirements**	**SBM input**
Heating set point (°C)	21	21	20	20
Cooling set point (°C)	25	25	25	25
Wall U (W/m^{2}K)	0.18	0.14	0.15	0.15
Floor U (W/m^{2}K)	0.13	0.17	0.15	0.18
Roof U (W/m^{2}K)	0.13	0.11	0.15	0.13
Glazing U (W/m^{2}K)	1.4	1.4	0.8	0.8
Infiltration at normal pressure (ach/hr)	0.511 (based on 5m^3/m^{2}h at 50 Pa)	0.511	0.042 (0.6 @ 50 Pa)	0.042
MVHR present (eff. = 0.9)	No	No	Yes	Yes
		SBM output		**SBM output**
Av. Env. U (W/m^{2}K)		0.28		0.23
Electricity demand (kWh/m^{2}a)		38 (not PE)		38 (not PE)
Heating required (kWh/m^{2}a)	**60 (Estimate for southern England)** (Pelsmakers, 2012)	**95** **(65 including solar and DHW gains estimate)**	**15 (Passivhaus maximum)** (Cotterell & Dadeby, 2012)	**28** **(3 – 11 including solar and DHW gains)**

The SBM embodied emission estimates are presented as summary statistics in Table 29. Table 30 shows a range of estimates found in the literature. The median embodied energy from the SBM is 10.5 kWh/m^{2}a, whereas the mean value in the literature is 32.8 kWh/m^{2}a. However, the latter figure is in primary, not final energy. The conversion between primary and final is location dependent, but values of 2–3 are common, indicating that the values are in reasonable agreement, and the values within the literature are definitely with the spectrum of values (Table 29) produced by SBM. In the case of embodied carbon, the discrepancy is larger: 5.5 kgCO_2e/m^{2}a for SBM) against 12 kgCO_2e/m^{2}a for the literature. Within the range of values given in the literature, however (Table 30), this discrepancy is small and hence acceptable.

Table 29: SBM embodied estimates (brick-based buildings).

	Embodied carbon ($kgCO_2e/m^2a$)	**Embodied energy (kWh/m^2a)**
Maximum	18.3	31.6
75^{th} percentile	6.6	12.2
Median	5.5	10.5
25^{th} percentile	3.8	8.7
Minimum	2.4	6.3

Table 30: Embodied estimates found in the literature.

EE kWh/a (primary)	**EC $kgCO_2e/m^2a$**	**References**
46.3	14.0	(Suzuki & Oka, 1998)
13.9	4.2	(Suzuki & Oka, 1998)
20.8	6.7	(Suzuki & Oka, 1998)
19.4	6.8	(Kim, et al., 2013)
27.1	9.2	(Kim, et al., 2013)
-	33.3	(Saynajoki, et al., 2011)
49.5	-	(Treloar, et al., 2001)
50.9	15.1	(Haynes, 2013)
-	6.3	(Yan, et al., 2010)
34.2	-	(Ezema, et al., 2015)50
33.3	-	(Paulsen & Sposto, 2013)
32.8	12.0	Mean

6.10. Postscript

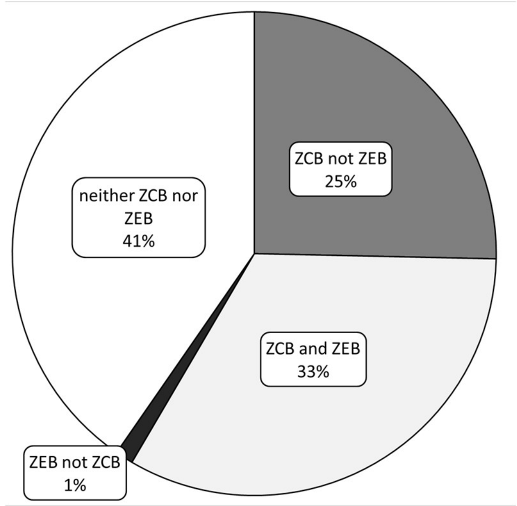
Chapter 6 builds on the ideas discussed in the preceding Chapters. Possible dwelling designs were combined with possible ZeroCC requirements in a variety of global locations creating a ZeroCC design space consisting of over 24 million design-requirement cases. While these cases do not include all possible standards and all possible buildings, the space created is sufficient to allow discussion of the relative size of the zero-carbon and zero-energy spaces, and some of the pertinent driving factors responsible for their differences in size.

Location was identified as an important feature from the perspective of both carbon emissions and energy demand, but for different reasons in each case. The implications of location were therefore investigated further, and the findings are presented in this postscript.

The results described so far in this Chapter have considered the whole population of SBM cases, including where the PV array is located remotely in Accra. However, most ZeroCC building conceptual frameworks assume that the PV array is located on the same site as the building (or nearby). The following discussion looks specifically at the population of SBM cases where the PV array is located onsite.

When the SBM population consists of only building system objects with onsite PV the ZCB and ZEB proportions are slightly lower, at 58% and 34% respectively. However, the proportions of ZCBs and ZEBs within the SBM population are very similar regardless of whether the conceptual framework includes remotely located PV or not (see Table 31).

Table 31: Classification of ‘PV onsite’ cases. Total population: 12,337,920



ZCB not ZEB	Case classified as zero carbon, but not zero energy
ZCB and ZEB	Case classified as both zero carbon and zero energy
ZEB not ZCB	Case classified as zero energy, but not zero carbon
neither ZCB nor ZEB	Case not classified as zero carbon or zero energy

In this scenario, the feature that is most predictive of both the zero-carbon, and the zero-energy target, is building height. Using Equation 2, the features in both the carbon and energy classification trees have been ranked (see Table 32). It is evident that similar features are important in both the carbon and energy trees, but the order of feature rankings differ. Height is still the most important feature, but this is followed by location for the carbon classification tree and occupant density for the energy tree.

Table 32: Ranking of features for carbon and energy classification trees when PV is located onsite.

Feature Rank	Carbon classification tree feature	Energy classification tree feature
1	Height	Height
2	Location	Occupants
3	Balance	Location
4	Occupants	Balance
5	Boundary	

The SBM population of building system objects with onsite PV arrays can be further differentiated by location. Carbon and energy classification trees were generated using the location specific SBM populations (with onsite PV). Subsequent ranking of the features identified shows that building height is almost always the most important feature. However, further features of importance vary depending on the characteristics of the location and whether the output under consideration is carbon or energy (see Table 33 and Table 34).

Table 33: Feature rankings for carbon classification trees for different locations when PV is located onsite.

	Location (order by increasing mean annual temperature - °C)					
	Oslo	Seattle	Carcassonne	Athens	Macapa	Mumbai
Temp.	5	9	13	19	26	27
Feature Rank						
1	Height	Height	Height	Occupants	Height	Height
2	Balance	Occupants	Boundary	Height	Occupants	Occupants
3	Boundary	Glazing	Balance	Balance	Balance	Balance
4	Glazing	PV spec.	Material		Boundary	Boundary
5			Occupants		Glazing	

A reasonably defined pattern is evident for the energy classification trees (see Table 34). For the colder locations, and ignoring the height feature, the properties of the thermal envelope are the features of greatest importance, with the size of glazing most highly ranked. As the mean annual temperature of the locations increases, occupant density and the distinction between a monthly and an annual energy balance rise up the rankings. The difference between including embodied energy in the conceptual framework, or not, only becomes important in the hottest locations.

A pattern is less evident in the carbon classification trees (see Table 33). Occupant density, the balance period, and the calculation boundary are still important in the hotter locations. However, the importance of thermal envelope properties is less clear in the colder locations. In the carbon classification trees, the only thermal envelope property identified is the size of glazing – for the two coldest locations, and one of the hottest locations. The embodied carbon properties of the PV array and building envelope are raised as features in Seattle and Carcassonne, although these features come low in the rankings.

Table 34: Ranking for energy classification trees for different locations when PV is located onsite.

	Location (order by increasing mean annual temperature - °C)					
	Oslo	**Seattle**	**Carcassonne**	**Athens**	**Macapa**	**Mumbai**
Temp.	**5**	**9**	**13**	**19**	**26**	**27**
Feature Rank						
1	Height	Height	Height	Height	Height/ Occupants	Height/ Occupants
2	Glazing	Glazing	Occupants	Occupants	Boundary	Boundary
3	Footprint	Occupants	Balance	Balance	Balance	Balance
4	Infiltration	Infiltration				
5		Balance				

Logistic regression was used to investigate the relationship between the different location characteristics and the odds of ZCBs and ZEBs occurring at those locations. Figure 37 and Figure 38 show that the logit(ZCB) for the locations depends on the CI of the local electricity grid, while the logit(ZEB) is related to the locations' mean annual temperatures.

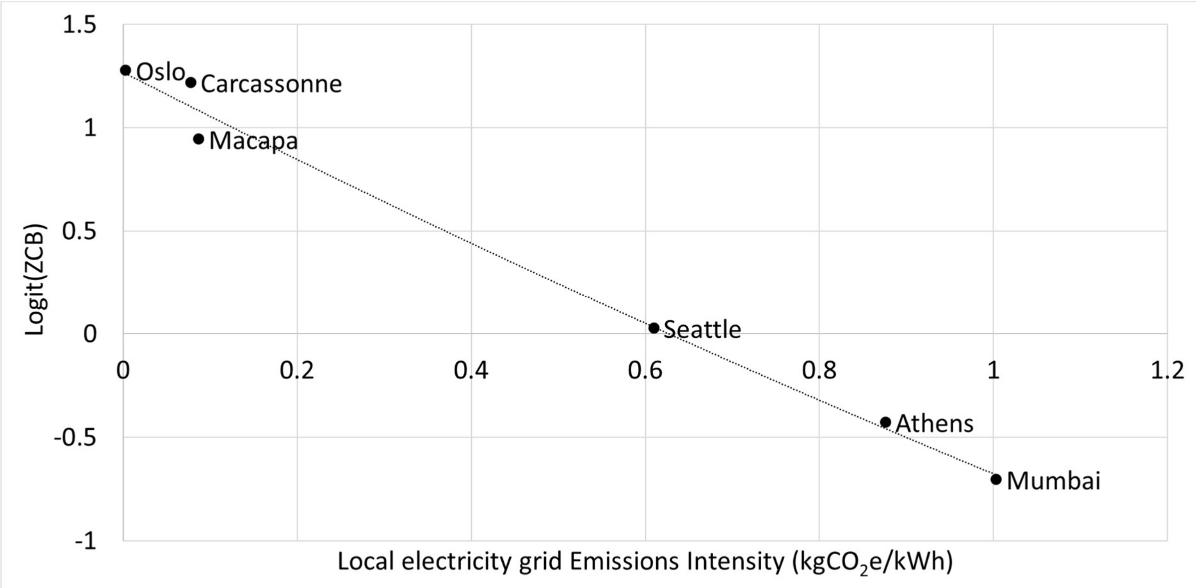


Figure 37: Graph showing the relationship between logit(ZCB) and electricity grid CI.

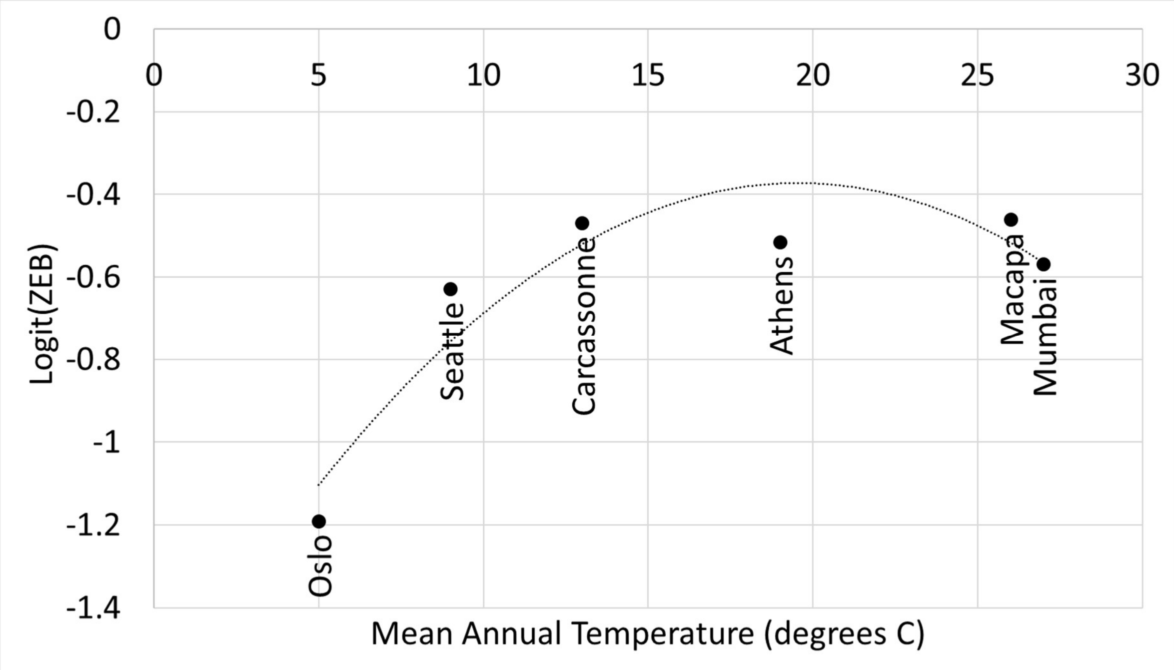


Figure 38: Graph showing the relationship between logit(ZEB) and mean annual temperature.

The odds ratios (OR) of ZCBs to ZEBs for each location is shown in Figure 39. As described in Section 7.7.2, OR(ZCB/ZEB) determines the likelihood of a ZCB occurring in the population compared with the likelihood of a ZEB occurring. It is evident that a negative logarithmic relationship exists between OR(ZCB/ZEB) and the carbon intensity of the local electricity. This is true whether the building system conceptual framework includes remotely located PV or not. This indicates that the lower the electricity grid CI, the greater the disparity between Odds(ZCB) and Odds(ZEB) under the application of the same building system conceptual framework.

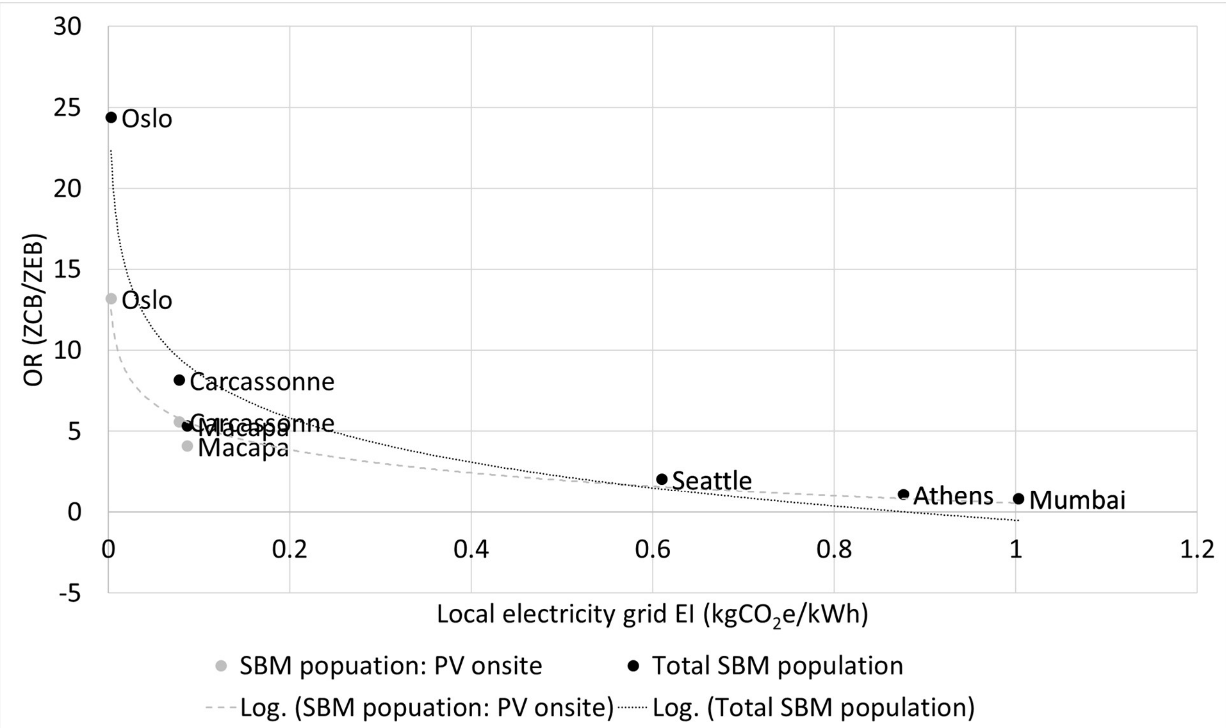


Figure 39: Graph showing the relationship between OR(ZCB/ZEB) and electricity grid CI.

It is evident from Figure 37 and Figure 38 that when the building system framework is applied in different locations (and assuming onsite PV only) the resulting difference in proportions of ZCBs and ZEBs is caused by different factors. The odds of ZCBs in the SBM case populations are determined by the local electricity grid CIs. The odds of ZEBs are instead largely caused by climate conditions (in Figure 38 mean annual temperature is the independent variable, but insolation levels at different locations follow a similar profile, and have a similar, and contributing, effect – see Appendix A5).

Notwithstanding the effects of climate change, the climates at different locations (temperature and insolation) are unlikely to change dramatically. This suggests that, if the zero-energy building conceptual framework described in this research is applied globally, the odds of ZEBs occurring the building population will always follow the pattern shown in Figure 38. However, electricity grid CIs around the world have changed over time, and it is the ambition of many governments that they will continue to reduce into the future (for example, as is the aim of the European Union (European Parliament, Council of the European Union, 2009)). Figure 37 suggests that such a reduction will automatically result in an increase in the odds of ZCBs occurring in the building population. In addition, Figure 39 indicates that as this happens the discrepancy between the odds of ZCBs occurring and the odds of ZEBs occurring will grow. This means that it will be increasingly difficult to justify the assumption that a zero energy design will produce a building that is equally beneficial from the perspective of climate change. As discussed in Section 1.5, the PHI has already suggested that, in a future where all energy is renewable, the primary energy (PE) factors used today to benchmark building energy demand will become meaningless (PE factors are currently used as a proxy for carbon emissions in frameworks which only account for energy – see discussion in Section 3.5).

Height is almost always the most important feature regardless of location or metric (carbon or energy). However, Table 33 and Table 34 show that the importance of other different building system design features does vary with location and metric. The feature rankings from the energy classification trees show an unsurprising result that the properties of the thermal envelope are important in ZEBs in cold climates. For the carbon classification trees however, although some thermal envelope properties (i.e. the size of glazing) arise as features of importance, a divide between cold and hotter climates is less clear for ZCBs. This further supports the idea that a building designed to be zero energy will not necessarily simultaneously be zero carbon. It is also clear from Table 33 and Table 34 that carbon emissions and energy demand associated with occupant use is almost always an important factor in the energy/carbon balance, and should therefore not be disregarded in any zero carbon building framework.

Chapter 7 describes in detail the Standard Building Model (SBM) that was developed to carry out this research.

Chapter 7. Development of the Standard Building Model (SBM)

To answer Research Question 3 many different modelled dwelling designs (3,840) were each assessed within a conceptual framework whose components could be varied. Given the resulting number of cases to be assessed, a Standard Building Model (SBM) was developed in MATLAB to create the theoretical dwellings and to carry out the subsequent assessments.

SBM is a simple heat and energy balance model which is based on an hourly time step. The SBM inputs include heat (and cooling) demand; electricity demand from plug loads; PV electricity generation; and embodied metrics associated with the fabric of the building (including the PV system). The SBM outputs are net energy demand and net carbon emissions.

This Chapter first describes the concepts that have been considered in the development of SBM and then details the components of SBM. Finally, the validation of SBM, and the methods used to analyse the data generated by SBM, are presented.

The development of the Standard Building Model was preceded by a number of models built to quantify the carbon emissions and energy demand associated with buildings, the Total Energy Model (TEM), the Virtual Building Model (VBM) and the Building Lifetime and Operational Carbon tool (BLOC). These models are described in Appendix A6, A8 and A10.

7.1. Heat demand in SBM dwellings

Heat transfer coefficients (U-values) are a measure of how easy it is for heat to escape through a building's thermal envelope (floor, roof, walls, windows). U-values are measured in watts (W) per square metre (m^2) per kelvin (K). This is a measure of how fast energy flows out (W) through the surface area of the thermal envelope (m^2) given a temperature difference between inside and outside (K). The lower the U-value, the better the thermal envelope, the less heat energy escapes, and the less heating is required. Increasing the amount of insulation in a wall or roof will lower the U-value and, for the same external temperature, reduce the heating required. Equally, for the same U-value, the smaller the temperature difference between the inside and outside, the less heat energy escapes, and the less heating is required.

A similar heat loss challenge is presented by the movement of air. Infiltration levels measure the speed of air movement (volume of air, m^3, per hour, h^{-1}) through the thermal envelope (through cracks and openings in the envelope of the building). In the case of cold climates in winter, the challenge is to minimise the loss of hot air from inside the thermal envelope.

In order to investigate the influence of heat loss components in a zero carbon building conceptual framework, the following properties of the building envelope were varied within SBM:

- Surface area of external walls – this depends on the building footprint and height.
- Depth of insulation in external walls – this depends on the U-values to be achieved and determines the EC and EE of the external walls.
- Surface area, and U-value of glazing – this influences the average thermal transmittance of the overall building envelope.
- Infiltration level – this determines the heat that is lost through air movement through the building envelope (as opposed to conduction).

The influence of heat gains in a zero carbon building conceptual framework were also investigated, from the perspective that, in a hot climate, heat gains are not beneficial, and may result in cooling (as opposed to heating) energy demand.

7.2. Electricity demand in SBM dwellings

Demand for electricity is largely tied to the dwelling occupants and their use of appliances. Electricity demand varies with the number of occupants, as well as with the type of household in question (see Table 35). Use tends to occur when the occupants are in the building, and so electricity demand is closely linked to occupant density. The use of electrical appliances results in heat gains which may usefully reduce demand for heating (when it is cold outside), although they may contribute to a cooling load in hot climates.

Table 35: Average annual electricity consumption per person in different household types. Source (Energy Savings Trust, 2012).

Household Type	Average electricity use per person (kWh/a)
Single pensioner	3,748
Single non-pensioner	3,926
Multiple pensioner	1,206
Household with children	1,350
Multiple household with no dependents	1,486

Electricity demand varies throughout the day, across the week, and during the year. (Knight, et al., 2007) provides an overview of European domestic electricity demand, and reports an average daily consumption of around 8 kWh per household in the summer. The paper presents daily profiles for both week days and weekend days during different seasons of the year. The daily pattern is fairly consistent (low demand overnight, rising during the day, with a peak in the evening), but it is evident that electricity demand fluctuates, generally rising during the winter and falling in the summer. A study of UK household electricity demand revealed a similar pattern (see Figure 40).

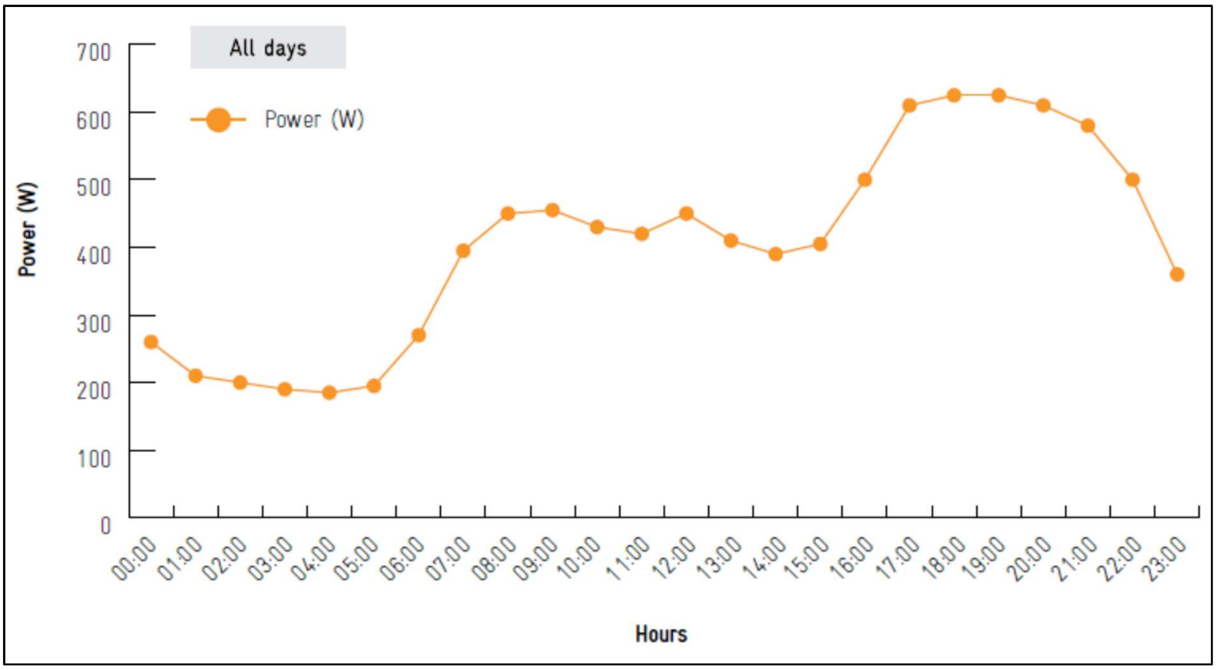


Figure 40: Daily profile for electricity use (excluding electric heating) in UK households. Source (Energy Savings Trust, 2012).

The fluctuation in electricity demand gives an indication of the challenge faced when designing a dwelling to be net zero-carbon or -energy, particularly if the aim is for energy demand to be satisfied by renewable electricity generated on site. Where PV is the electricity generation method, there will not only be a daily demand and generation mismatch, but the time difference between summer peak generation and winter peak demand is also a potential hurdle. For example, peak domestic UK electrical demand is around 650W per household (Energy Savings Trust, 2012) and occurs at about 7pm on a winter day when it is dark.

In order to investigate the influence of different levels of electricity demand in a zero carbon building conceptual framework, occupancy densities, and therefore levels of electricity demand, were varied within SBM. Electricity demand resulting from cooling demand depends on the internal temperature, regardless of occupancy density.

7.3. Embodied carbon and energy in SBM dwellings

The embodied carbon and energy tied up in the fabric of a building is a function of the types, and quantities, of materials used in the construction of the building. The quantity of materials is dependent on the size of the building, and, in the case of insulation materials, the thermal transmittance design requirements (i.e. lower external wall U-values require greater quantities of insulation). In addition, as discussed in Section 5.7, embodied carbon and energy is tied up in the fabric of the renewable energy generating technology (in this case the PV array) that forms part of the zero carbon building system.

In the zero carbon building conceptual framework investigated in this work embodied carbon is included in the building systems' net carbon emissions. As the size (and shape) of the building varied, so the quantity of materials (including the size of the PV array) varied. In addition, as well as the varying the envelope dimension properties, as outlined in Section 7.1 above, the principle construction materials from which the building envelopes were constructed were varied. SBM dwellings were modelled as being constructed of either brick and block, or timber and straw.

SBM embodied metrics are calculated based on the specification of the building materials, and the size of the building and PV array. These values are converted into annual, or monthly, equivalents in order to allow comparison between operational and embodied metrics. The building life is assumed to be 60 years, and the PV array and glazing are assumed to have lifetimes of 30 years (see Appendix A15).

Two conceptual framework boundaries were applied to the assessment of the buildings. *Operational* includes only the carbon emissions, or energy demand, associated with the operation of the buildings (e.g. heating and electricity demand); *Operational + Embodied*, also includes the carbon emissions, or energy, used to create (or stored in, where carbon sequestration is applicable) the fabric of the building. In both cases PV electricity generation offsets overall energy demand or carbon emissions.

7.4. PV generation in SBM dwellings

The amount of electricity generated by a PV array depends on the size of the PV array (surface area) and the amount of sunlight that it is exposed to. Within the PHI's Passivhaus Plus and Premium conceptual frameworks, PV generation requirements are measured against the building footprint, as opposed to the internal floor area. The idea behind this approach is that a building covers an area of land (equal to the building footprint) which can no longer be used for any other purpose, including renewable energy generation. The addition of a roof-mounted PV array, of the same size as the building footprint, effectively reinstates the land as a site for renewable energy generation.

In the zero carbon building conceptual framework investigated in this work, every building system included a PV array that is the same size as the building footprint. This meant that the building system PV array size varied with the length and/or width of the building. As well as the usual approach taken, whereby the PV array is part of the physical building system (i.e. roof-mounted), this work investigated a conceptual framework in which the building system was not limited by a physical boundary, and the PV array could also be located offsite in a different country, closer to the equator. This meant that, within the zero carbon building conceptual framework, the PV array forming part of each building system could be exposed to different amounts of sunlight, and connected to different electricity grids.

Two different balance periods were applied to the assessment of the PV generation / energy demand balance. In the *Annual* scenario, excess PV generation occurring at one time in the annual cycle (for example, in summer) is used to offset demand at another point in the cycle (for example, in winter). In the *Monthly* scenario, excess PV generation must be used within the monthly cycle. For calculation purposes, any surplus left at the end of the month is lost, meaning that summer generation cannot be used to offset winter demand. In both scenarios excess PV generation is assumed to be stored in the national grid (following the principle described in Section 1.4), or in onsite batteries.

7.5. The Standard Building Model

The Standard Building Model (SBM) consists of a number of MATLAB programmes (see Appendix A12) which use imported building specification and location data to calculate the energy demand and carbon emissions for one building system. The SBM programme sequence is as follows:

assignMatrices.m

See Appendix A14 for the SBM Matlab code.

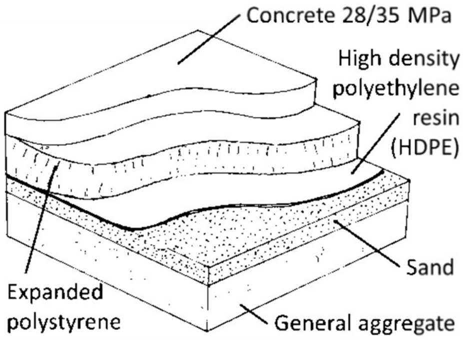
Initial wall, floor, roof and glazing data are imported from Excel files as matrices containing information about the materials (including quantities) used in the construction, and their respective thermal conductivities (W/mK), embodied carbon values ($kgCO_2e/m^2$) and embodied energy values ($MJ_{primary}/m^2$).

The materials specified for the different elements of the building envelope are matched as closely as possible with equivalent materials in the Inventory of Carbon and Energy (Hammond, et al., 2011) from which embodied values are obtained. Thermal conductivities for the same materials are primarily drawn from BS EN ISO 10456 (BS EN ISO 10456, 2007), but also from The Environmental Design Pocketbook (Pelsmakers, 2012) where not otherwise available.

The ground floor

The ground floor is modelled as a solid floor construction according to the specification for the UK Passivhaus (Passive-on, 2007b). The U-value of the floor is calculated according to BS EN ISO 13370 (BS EN ISO 13370, 2007) and assumes the ground below has the thermal properties of sand or gravel (see Table 36).

Table 36: Ground floor construction details for all buildings. Embodied metrics from Hammond G., Jones, Lowrie, & Ise (2011).

	Ground floor	
Envelope element		
Materials	Structure: Concrete; HDPE; Sand; General aggregate	Insulation: Expanded polystyrene
Total depth (m)	0.8	Variable
Total resistance (m^2K/W)	0.6	5.3 (@ 185 mm)
EC* per m^2 ($kgCO_2e$)	55	15 (@ 185 mm)
EE** per m^2 (kWh)	508	410 (@ 185 mm)

* EC = Embodied carbon ** EE = Embodied energy

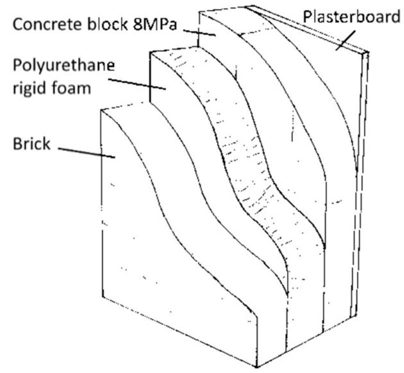
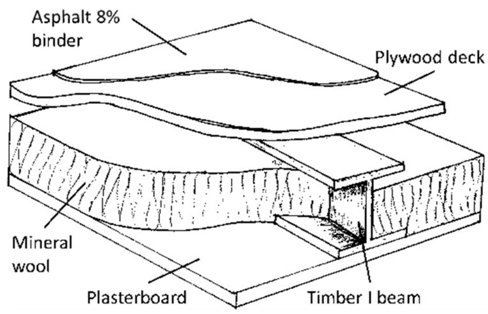
See Appendix A42 for the ground floor data.

The external walls

The external walls are modelled either as brick and block walls (with a positive embodied carbon value), or straw bale walls (with a low, or negative, embodied carbon value).

The material specifications for 'brick' buildings are based on the UK Passivhaus in (Passive-on, 2007b). Brick buildings consist of brick and block external walls (see Table 37), mineral wool roof insulation (see Table 37) and concrete intermediate floors (see Table 38). The brick walls are modelled with insulation fully within the cavity according to the specification for the UK Passivhaus (Passive-on, 2007b). The U-value of the walls is calculated according to BS EN 6946:2007 (BS EN ISO 6946, 2007).

Table 37: Envelope construction details for brick buildings. Embodied metrics from Hammond G., Jones, Lowrie, & Ise (2011).

	External wall		**Roof**	
Envelope element				
Materials	Structure: Brick; Concrete block; Plasterboard	Insulation: Polyurethane rigid foam	Structure: Asphalt; Plywood; Timber I beam; Plasterboard	Insulation: Mineral wool
Total depth (m)	0.2	Variable	n/a	Variable
Total resistance (m^2K/W)	0.7	4.3 (@ 100 mm)	n/a	8.3 (@ 300 mm)
EC* per m^2 ($kgCO_2e$)	54	13 (@ 100 mm)	17	12 (@ 300 mm)
EE** per m^2 (kWh)	679	305 (@ 100 mm)	351	149 (@ 300 mm)

* EC = Embodied carbon ** EE = Embodied energy

Table 38: Intermediate floor construction details for brick buildings. Embodied metrics from Hammond G., Jones, Lowrie, & Ise (2011).

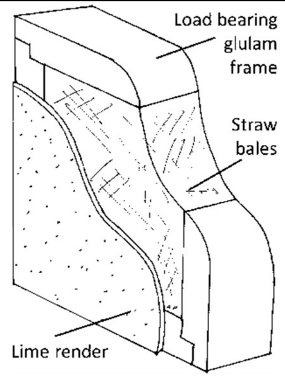
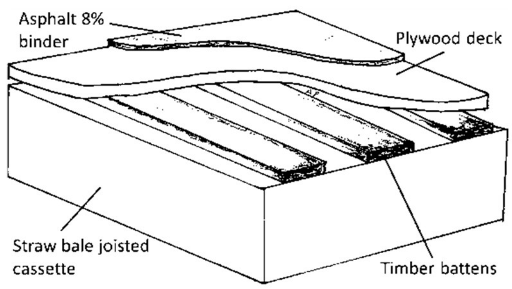
Intermediate floor construction: **Brick buildings**	**EC*** **($kgCO_2e/m^2$)**	**EE** per m^2** **(MJ_{prim})**
Structure materials: Cement : sand screed; lightweight concrete blocks; Precast concrete T beam	34	229

* EC = Embodied carbon ** EE = Embodied energy

The construction details and embodied metrics for 'straw' buildings are based on (Pelly & Mander, 2014) and (Maskell, et al., 2015). Straw buildings consist of straw bale external walls and a straw bale roof (see Table 39) and timber intermediate floors (Profideck in Pelly & Mander (2014) – see Table 40).

Straw buildings are assessed under two assumptions: carbon sequestration is applicable to timber and straw building components (i.e. embodied carbon for such elements is negative); or carbon sequestration is not applicable at all (i.e. embodied carbon for such elements is not less than zero).

Table 39: Envelope construction details for straw buildings.

	External wall		**Roof**	
Envelope element				
Materials	Structure: Glulam frame; Lime render	Insulation: Straw bales	Structure: Asphalt; Plywood; Timber battens	Insulation: Straw bale cassettes
Total depth (m)	Variable		n/a	Variable
Total resistance (m^2K/W)	5.6 (@ 400 mm)		n/a	4.2 (@ 300 mm)
EC_{Seq}* per m^2 ($kgCO_2e$)	-217 (@ 400 mm)		n/a	-68 (@ 300 mm)
EC_{exSeq}** per m^2 ($kgCO_2e$	28 (@ 400 mm)		13	19 (@ 300 mm)
EE*** per m^2 (kWh)	779 (@ 400 mm)		284	949 (@ 300 mm)

* EC_{Seq} = Embodied carbon *with* carbon sequestration *** EE = Embodied energy

** EC_{exSeq} = Embodied carbon *no* carbon sequestration

Table 40: Intermediate floor construction details for straw buildings.

Intermediate floor construction: Straw buildings	**EC* (*with* carbon sequestration) ($kgCO_2e/m^2$)**	**EC* (*no* carbon sequestration) ($kgCO_2e/m^2$)**	**EE** (kWh/m^2)**
Structure materials: Timber intermediate floors (Profideck)	-92	26	207

* EC = Embodied carbon ** EE = Embodied energy

See Appendix A43 and A44 for the wall data.

The roof

The roof U-value is derived from the U-values of the (horizontal) insulation and plasterboard. It is assumed that neither the PV array, nor anything else on the roof, forms part of the thermal envelope.

See Appendix A45 for the roof data.

The windows

The windows are assumed to be PVC double glazing with an EC of 125 kgCO_2e per 1.2m x 1.2m unit.

See Appendix A46 for the window data.

SBMconstants.m

The constants used in the SBM calculations are defined. For example, the occupied heating and cooling temperatures (Appendix A15 lines 16 and 21), and the carbon intensities (CIs) of electricity and the heating fuel (lines 30 – 35).

Heating is used to raise the internal temperature to the heating set point and demand is reduced by hourly metabolic heat gains, and those from electrical equipment. Domestic hot water is not accounted for in the SBM energy demand calculations, so related gains are not included either.

Cooling is used to reduce the internal temperature to the cooling set point. It is assumed that all windows can be opened, allowing the internal and external temperatures to reach equilibrium. This means that no cooling is active when the external temperature is below the cooling set point. The cooling system in SBM has a coefficient of performance of 0.5814, based on Szokolay (2008), and is powered by electricity from the local grid (with the associated local electricity grid CI for carbon calculations).

The internal temperature set points for all buildings, and the heating fuel carbon intensity are shown in Table 41.

Table 41: Building heating and cooling characteristics.

Building component	Specification
Occupied heating set point (°C)	18
Unoccupied heating set point (°C)	13
Occupied cooling set point (°C)	25
Unoccupied cooling set point (°C)	30
Heating fuel	Whichever has the lower CI: UK gas (0.216 kgCO_2e/kWh) or electricity from the local electricity grid.
Cooling fuel	Electricity from the local electricity grid.

See Appendix A15 for the SBM Matlab code.

SBMbuildSpec.m

Calculations to determine the building dimensions. The building footprint, width and number of storeys (Appendix A16, lines 3 – 5) can either be specified for one SBM building model, or a range of values can be used as inputs to run SBM many times (see Table 42), generating buildings of different sizes.

Table 42: Ranges of building dimensions used to generate SBM building objects.

	Variable	Value range / Categories
	Footprint (m^2)	45 – 450 m^2 in steps of 45 m^2
	Width (m)	Limitations were placed on the aspect ratios permitted (to avoid modelling unreasonably narrow and/or tall buildings). Valid building widths were calculated using aspect ratios 1, 0.5, 0.25 and 0.125 and Equation 3.
	Height (storeys)	Equation 3: $Building\ width = \sqrt{aspect\ ratio \times building\ footprint}$ The modelled buildings have different wall depths, so an additional requirement was included that the internal floor area for one storey must be greater than 25 m^2. 1, 2, 4, 8, 16 and 32 storeys were modelled, with the same limitation on aspect ratios.

See Appendix A16 for the SBM Matlab code.

wallU1.m, floorU1.m, roofU1.m

Calculations to determine the U-values (W/m^2K) and embodied carbon values ($kgCO_2e/m^2$) of the external walls (Appendix A17), the ground floor (Appendix A18) and the roof (Appendix A19) using the imported building envelope element data.

The buildings were modelled with different heat loss/gains characteristics. Multiple opaque envelope element U-values are achieved by modelling different depths of insulation in the external walls, ground floor and roof (see Table 43 and Table 44). In order to maintain a consistent approach to thermal envelope properties, the depths of insulation in the ground floor and roof vary in a similar manner to that in the external walls (i.e. greater depths of insulation in the walls are coupled with greater levels of insulation in the roof and ground floor). Heat transmittance is calculated using BS EN ISO 13370 (2007).

Table 43: U-values in external walls.

External wall U-value (W/m^2K)	Notes
0.18	Compliant with UK Building Regulations (HM Government, 2013)
0.15	As suggested to comply with the Passivhaus standard (Cotterell & Dadeby, 2012)
0.12	As suggested for a detached house to comply with the Passivhaus standard (Cotterell & Dadeby, 2012)
0.10	As suggested for spread out detached house to comply with the Passivhaus standard (Cotterell & Dadeby, 2012)

Table 44: U-values and insulation depths in opaque elements other than external walls.

External wall U-value (W/m^2K)	Brick SBM buildings				Straw SBM buildings			
	Ground floor		Roof		Ground floor		Roof	
	I*	U**	I*	U**	I*	U**	I*	U**
0.18	110	0.18	220	0.15	95	0.19	380	0.17
0.15	130	0.16	260	0.13	119	0.17	475	0.14
0.12	180	0.13	360	0.09	150	0.14	600	0.11
0.10	220	0.11	440	0.08	175	0.13	700	0.10

* I = Insulation depth (mm) ** U = U-value (W/m^2K)

winArea1.m

Calculations to determine the total area of glazing (m^2), the average U-value of the glazing (W/m^2K) and the embodied carbon of the glazing ($kgCO_2e/m^2$). Heat losses/gains via glazing are determined by the glazing U-values and glazing areas shown in Table 45.

Table 45: Ranges of glazing properties used to generate SBM building objects.

	Variable	Value range / Categories	
	Glazing area	10, 20, 40 and 80 % of the external walls	
	Glazing U-value (W/m^2K)	1.4	Complies with UK Building Regulations 2014 (HM Government, 2013)
		0.8	Passivhaus compliant (Cotterell & Dadeby, 2012)
	Regardless of U-value, embodied metrics for glazing do not change.	0.68	Based on the ULTRA range (Green Building Store, 2017)

See Appendix A20 for the SBM Matlab code.

editWinArea.m

Programme to change the area of glazing (as a percentage of wall area) from the original specification. Original specification must have glazing > 0% of walls. After the glazing percentage is changed *winArea1.m* runs again.

See Appendix A21 for the SBM Matlab code.

thermEnv1.m

Calculations to determine the overall U-value of the building envelope (Appendix A22, line 19), the heat flow rate (W/K) through the building envelope (line 20) and the total building envelope embodied carbon (line 23).

The internal floor area (IFA) is calculated based on the dimensions of the building and the depth of the walls. The internal floor area of one storey must be greater than 25 m^2 (lines 28 – 32).

The infiltration rate (air changes per hour – ach) is defined (lines 50 – 58), and the ventilation heat flow rate (W/K) is calculated (line 62).

The buildings were modelled with three levels of air infiltration. The heating system present in the SBM buildings depends on the levels of air infiltration. A traditional heating system is present when air infiltration levels are high, but is replaced by a mechanical ventilation with heat recovery (MVHR) unit when air infiltration is low.

See Appendix A22 for the SBM Matlab code.

EnvEE.m

See Appendix A23 for the SBM Matlab code.

Runs programmes ***wallEE.m*** (Matlab code in Appendix A24), ***floorEE.m*** (Matlab code in Appendix A25), ***roofEE.m*** (Matlab code in Appendix A26) and ***winEE.m*** (Matlab code in Appendix A27) to calculate the (non-primary) embodied energy of the building envelope components (kWh/m^2) (lines 1 – 4). Calculates the total building envelope embodied energy (line 14).

exTemp.m

Location temperature data is imported from an Excel file as a matrix describing the average daily maximum and minimum temperatures (°C) for each month of the year. This data is used to generate hourly external temperatures for the average day in each month of the year (line 18).

Six locations were chosen to cover a range of external temperatures (see Appendix A47), insolation levels (see Appendix A48), and electricity grid CIs—simulating fossil fuel to renewables based societies.

Hourly external temperature data and insolation levels for the different locations are based on data from NASA (NASA, 2015).

Temperature data is provided in the form of average daily maximum and minimum temperatures for each month in the year. Hourly temperatures are extrapolated from this by assuming a daily sinusoidal pattern based on the maximum and minimum temperatures.

Insolation data is provided in a number of forms: each month's daily average insolation incident on tilted surfaces (for optimum annual PV generation); and monthly average total solar radiation incident on a horizontal surface in three hour intervals. Hourly insolation on tilted surfaces is calculated using the horizontal and tilted surfaces data, and then multiplied by a uniformly distributed random number (between 0 and 1) to reflect the variable nature of cloud cover (see Equation 4 and Equation 5).

Equation 4: Calculation for 3-hourly insolation incident on an optimally tilted surface.

$$3hOpt_i = 3hHoz_i\left(\frac{dAvOpt}{dAvHoz}\right)$$

Where;

$3hOpt_i$	(kW/m^2)	=	Insolation at 3-hourly interval i incident on an optimally tilted surface pointed towards the equator (see Table 46 for tilt angle)
$3hHoz_i$	(kW/m^2)	=	Insolation at 3-hourly interval i incident on a horizontal surface
i		=	3-hourly interval, 1 = 00:00-03:00; 2 = 03:00-06:00;…8 = 21:00-00:00
$dAvOpt$	(kWh/m^2)	=	Daily average insolation incident on an optimally tilted surface pointed towards the equator
$dAvHoz$	(kWh/m^2)	=	Daily average insolation incident on a horizontal surface

Equation 5: Calculation for randomised hourly insolation on an optimally tilted surface.

$$hOpt_h = 3hOpt_i[a_m + r(b_m - a_m)]$$

Where;

$hOpt_h$	(kWh/m^2)	=	Randomised hourly insolation incident on an optimally tilted surface pointed towards the equator at hour h
h		=	Hour of the day
			For $j = 1\ to\ 8$, $i = j$ when $(3j - 2) \leq h \leq 3j$
a_m	(kWh/m^2)	=	$dAvHoz_m + (dAvHoz_m \times diffNeg_m)$
b_m	(kWh/m^2)	=	$dAvHoz_m + (dAvHoz_m \times diffPos_m)$
r		=	Random number in the range [0,1]
m		=	Month of the year, 1 = Jan; 2 = Feb;…Dec = 12
$diffNeg$	(%)	=	Maximum negative difference from monthly averaged insolation on a horizontal surface
$diffPos$	(%)	=	Maximum positive difference from monthly averaged insolation on a horizontal surface

See Appendix A28 for the SBM Matlab code.

annInsoUni1.m

See Appendix A29 for the SBM Matlab code.

Location insolation data is imported from an Excel file as a matrix describing insolation incident on a surface tilted for annual average optimal PV generation facing the equator (kW/m^2). This is based on insolation measured at three-hourly intervals incident on a horizontal surface. Also included in the matrix is data regarding the maximum and minimum percentage differences from the monthly average levels of insolation. The data in the matrix is used to generate random hourly insolation levels across a week for each month of the year.

Buildings are modelled with a PV array covering the entire roof, angled for optimum annual electricity generation (see Table 46). The size of the PV array depends on the shape of the building, and determines the amount of electricity generated, and the total embodied metrics for PV.

Table 46: PV tilt angle for optimum annual generation at each location. It is assumed that the PV always faces the equator.

City	Athens	Carcassonne	Macapa	Mumbai	Oslo	Seattle	Accra
PV tilt angle (°) (NASA, 2015)	37	43	0	19	59	47	5

See Appendix A48 for the insolation data.

PV1.m

Calculations to determine the total embodied metrics of the PV array (lines 7 and 9 respectively). Calculations to determine the hourly (random) PV electricity generation across a week for each month of the year (line 18) based on the hourly insolation levels generated in *annInsoUni1.m*. The output of *PV1.m* is shown graphically in Figure 41.

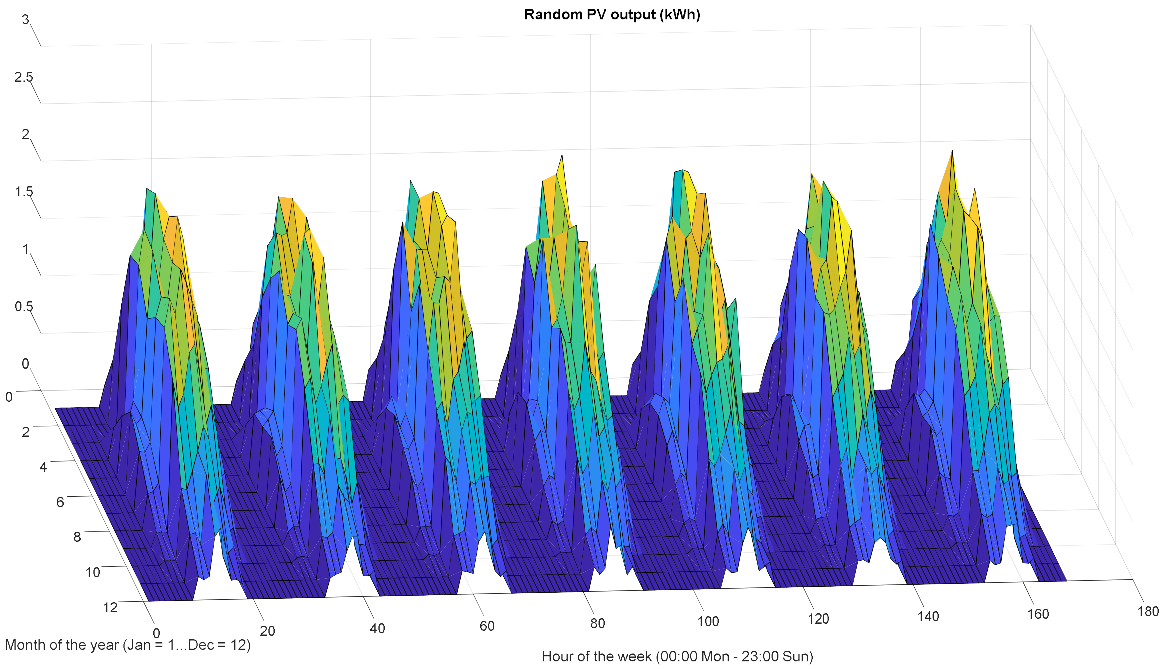


Figure 41: Output from SBM *PV1.m*. Hourly PV generation across a typical week for each month of the year for a 45m^2 PV array located in Watford, UK.

As identified in Section 5.7, the embodied metrics associated with the manufacture of PV modules are not well known. However, PV plays an important role in a zero building, in terms of offsetting demand, and also in its contribution to the total embodied value. In order to investigate the impact of this diversity, two different PV specifications were applied: PV with low embodied metrics, based on (Mann, et al., 2014), to simulate the use of PV modules manufactured in a lower carbon economy (e.g. Europe); and PV with high embodied metrics, based on (Nawaz & Tiwari, 2006), to simulate the use of PV modules manufactured in a higher carbon economy (e.g. Asia) (see Table 47 for the embodied values).

Table 47: Range of embodied metrics for PV used to generate SBM building system objects.

	Variable	Value range / Categories		
	PV specification		Embodied carbon ($kgCO_2e/m^2_{PV}$)	Embodied energy (kWh/m^2_{PV})
		Low embodied metrics	149	241
		High embodied metrics	953	318

The embodied metrics associated with PV are only relevant where the calculation boundary includes both operational and embodied metrics. The carbon emissions, or energy demand, associated with the transportation of materials and manufactured products is outside the scope of this work.

See Appendix A30 for the SBM Matlab code.

domThermal1.m

See Appendix A31 for the SBM Matlab code.

Runs programmes to determine heating profiles (*domOcc.m*), heat losses (*annualTemp1.m*) and cooling demand (*annualTemp2.m*).

domOcc.m

See Appendix A32 for the SBM Matlab code.

Generates a matrix to describe the hourly heating pattern over the week (occupancy/heating profile. The pattern is based on the Energy Follow-Up Survey (BRE, 2013) which found that the average number of hours that the heating is on for a centrally heated household is around seven hours; where the heating is on twice per day this is typically for two hours in the first period and five hours in the second period.

annualTemp1.m

See Appendix A33 for the Matlab code.

Applies the heating set points defined in *SBMconstants.m* to the hourly heating (occupancy) pattern generated in *domOcc.m* (line 4), and, using the external temperature pattern described in *exTemp.m*, calculates the heat loss through the building envelope (line 43 - 63) and through infiltration losses (line 36 – 39). The output of *annualTemp1.m* is shown graphically in Figure 42.

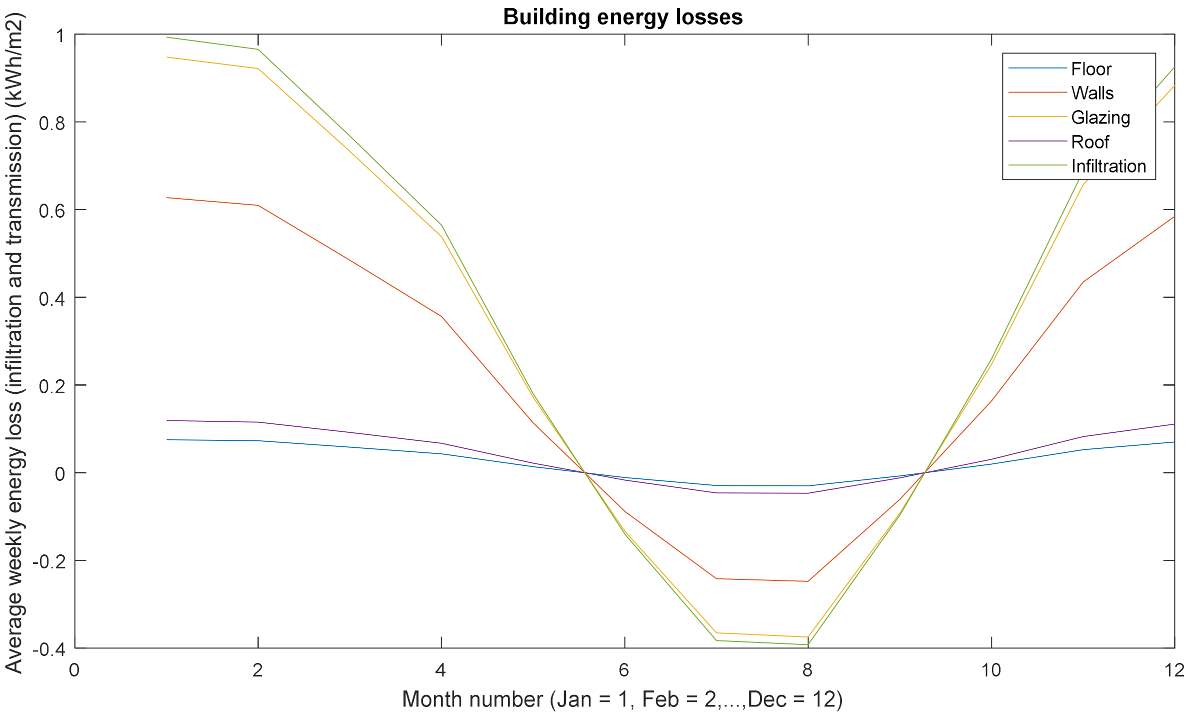


Figure 42: Output from *annualTemp1.m*. Plot showing the average weekly energy loss through the building envelope (transmission and infiltration) for each month of the year for a building located in Watford, UK with characteristics as detailed in Table 48. Note that for these building characteristics (size of glazing and U-value) transmission heat loss through the glazing is similar to infiltration loss. Figure 43 shows how the relative significance of heat loss through glazing and infiltration changes depending on how airtight the building is.

Table 48: SBM building characteristics for output shown in Figure 42.

Building element	**Ground floor**	**External walls**	**Glazing**	**Roof**
U-value (W/m^2K)	0.14	0.19	1.40	0.11
Surface area (m^2)	45	139	29	45
Infiltration rate (air changes per hour)	0.70			
Heating degree hours (kKh)	43			
Total thermal energy loss (kWh/m^2a)	52			

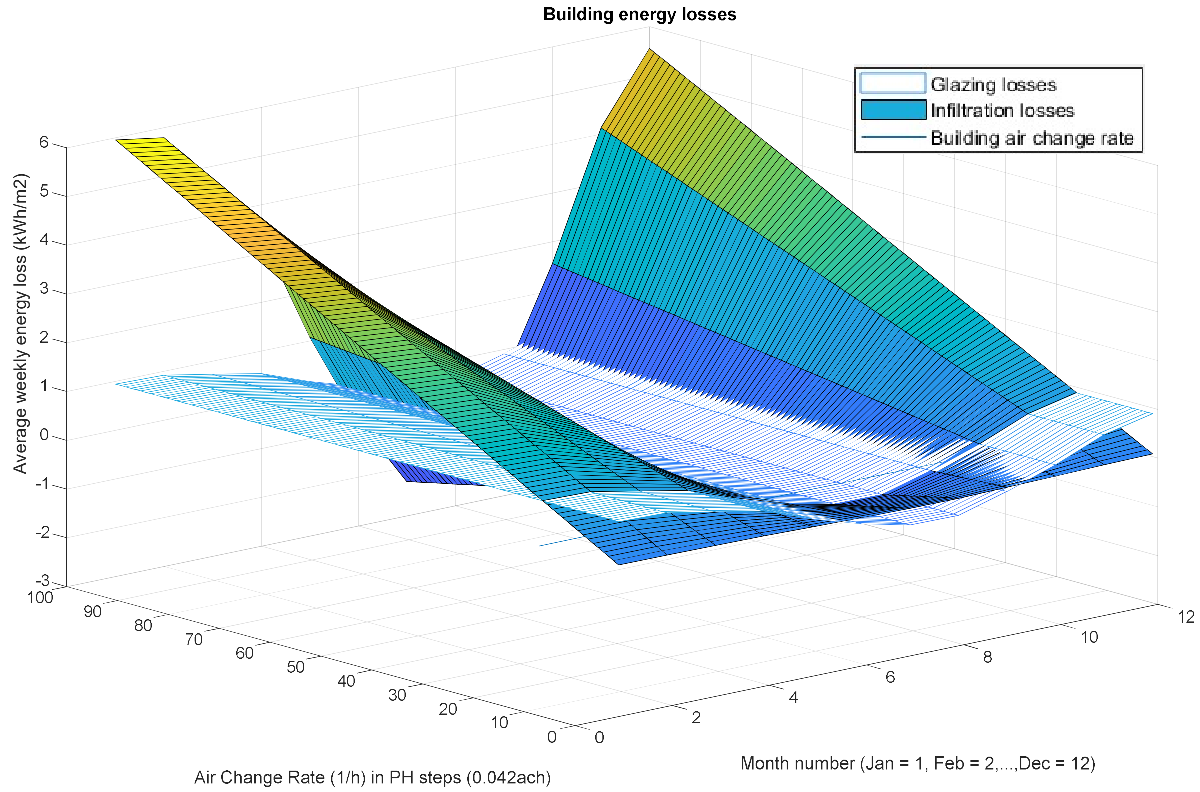


Figure 43: Plot showing a comparison of energy losses through glazing (surface area of 29 m^2) and infiltration (variable air change rates) for a building located in Watford, UK for an average week in each month of the year. The Building air change rate marked (blue line) is that for the building described in Figure 42 and Table 48.

annualTemp2.m

See Appendix A34 for the Matlab code.

Applies the cooling set points defined in *SBMconstants.m* to the hourly heating (occupancy) pattern generated in *domOcc.m* (line 6), and, using the external temperature pattern described in *exTemp.m*, calculates the beneficial heat loss through the building envelope (line 36 - 56) and through infiltration losses (line 29 – 32).

SBMdomDem.m

See Appendix A35 for the SBM Matlab code.

SBM assumes that electricity demand is tied to occupancy levels (mainly plug loads). Demand rises and falls throughout the day, with a constant base load included to account for appliances on standby mode or running continuously (e.g. fridges). The electricity demand profile is based on the patterns of demand identified in (Knight, et al., 2007), and varies across the day, the week and the year (see Figure 44). The overall electricity demand level is based on the usage of a typical UK family of four (Energy Savings Trust, 2012), with a value of 1,350 kWh/a per person.

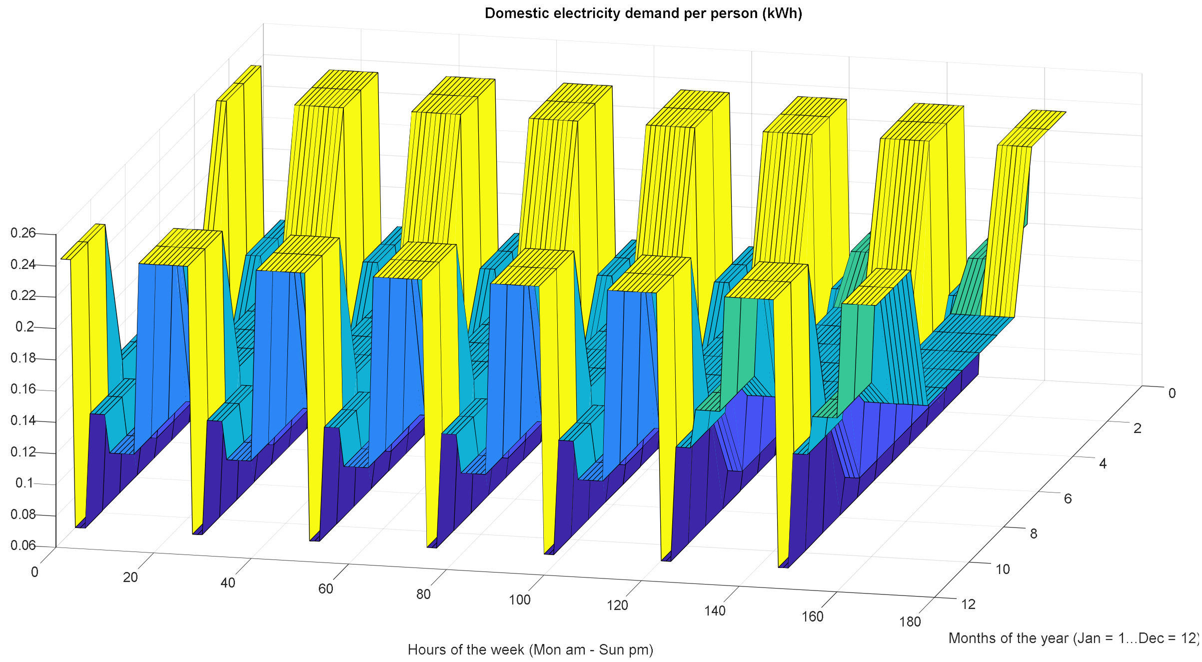


Figure 44: Plot showing the SBM domestic electricity demand profile across the hours of the week and the months of the year.

The buildings were modelled with three levels of occupancy (see Table 49). Electricity demand from plug loads is tied to the occupants, as are the associated heat gains, and metabolic heat gains.

Table 49: SBM occupancy densities

Occupancy	Notes
No occupants	An empty building. SBM assumes that the building will still need to be heated/cooled, but there are no metabolic heat gains. In addition, there is no electricity demand (or associated heat gains) from plug loads.
35 m^2/person	Occupancy density as assumed in the Passivhaus standard (Cotterell & Dadeby, 2012)
20 m^2/person	Occupancy density based on family of four in a 'typical' UK house (as in Section 4.4)

Hourly electricity demand profile data is imported from an Excel file (see Appendix A49). The daily profiles are based on (Knight, et al., 2007). Occupant type demand levels are based on the Powering the Nation report (Energy Savings Trust, 2012). This data is used to generate weekly electricity demand profiles for each month of the year (line 59).

The number of occupants can be defined based on a specified number of people, or an occupancy density (people/m^2_{IFA}) (lines 66 – 70).

Calculations to determine the total electricity demand (line 72) and the hourly net electricity demand (demand minus PV generation) (line 86).

See Appendix A49 and A50 for the electricity demand data.

domHG1.m

See Appendix A36 for the SBM Matlab code.

Similar calculations as in *SBMdomDem.m*, but to determine heat gains from electrical appliances. Heat gain calculations are based on the method used in Passivhaus assessments (Cotterell & Dadeby, 2012), and calculations to determine heat gains from occupants (Korolija, et al., 2013) (line 71 – 74).

See Appendix A51 and A52 for the heat gains data.

domHeating1.m

See Appendix A37 for the SBM Matlab code.

Calculations to determine the heating required to maintain the heating set point given the heat losses through infiltration and the building envelope, and heat gains from appliances and metabolic heat gains (line 29). When the heating system is on, it is assumed that the building is fully occupied and maximum (100%) metabolic heat gains are present (line 24). Otherwise metabolic heat gains are spread evenly over the remaining hours with their total contribution determined by the utilisation factor in *SBMconstants.m*, line 27 (lines 25 and 26).

domCooling1.m

See Appendix A38 for the SBM Matlab code.

Calculations, based on *domHeating1.m*, to determine when cooling is required to maintain the cooling set point. Cooling is required when net heat gains (in relation to the cooling set point) are positive, heat losses (in relation to the heating set point) are negative and the external temperature is above the cooling set point - i.e. opening windows will not cool the building (line 18). The coefficient of performance for the cooling system (line 25) is based on Introduction to Architectural Science (Szokolay, 2008).

SBMZCB.m

See Appendix A39 for the SBM Matlab code.

Calculations to determine the net building carbon emissions (Zero Carbon Balance) and energy demand (Zero Energy Balance).

See Appendix A40 for an example of SBM output.

7.6. Validation of the SBM

The Standard Building Model (SBM) calculates the carbon emissions and energy demand associated with a dwelling based on inputs that describe the dwelling's electricity demand, heating (and/or cooling) demand, carbon and energy embodied in the fabric of the building and carbon and energy savings resulting from PV generation.

In SBM, the dwelling electricity demand is dependent on the occupant density (i.e. electricity demand level input is based on kWh per person). The demand level values are based on data from (Energy Savings Trust, 2012), and the domestic electricity demand profile is based on (Knight, et al., 2007). The other components of SBM (heat demand, embodied metrics and PV generation), are modelled in SBM using a number of sources of data. This section considers the appropriateness of the data used, and the reliability of the SBM outputs.

7.6.1. Weather data

SBM uses weather data sourced from NASA as inputs to describe the environmental conditions (external temperature and insolation) that the dwellings are subject to on an hourly basis. The NASA data available come directly from, or are calculated using, meteorological parameters taken from NASA's Modern Era Retro-analysis for Research and Applications (MERRA-2) assimilation model (Stackhouse, et al., 2018). The MERRA-2 model uses satellite measurements, along with surface observations, spanning the period 1981 to the present day, to generate global estimates of a range of atmospheric variables. The data are available on a global grid with a spatial resolution of 0.5º latitude by 0.5º longitude.

Weather data may alternatively be sourced from surface observations. However, this data is only available for locations for which relevant records have been kept. For example, Typical Meteorological Year 3 (TMY3) data files provide hourly 'typical' weather data for 1,020 locations in the USA recorded in the period 1991-2005 (EnergyPlus, 2018) (Wilcox & Marion, 2008). Similarly, International Weather for Energy Calculations (IWEC) data files provide hourly 'typical' weather data for 227 locations outside the USA and Canada derived over approximately 18 years (1982-1999) (EnergyPlus, 2018) (ASHRAE, 2001).

7.6.2. Heat demand

In SBM hourly external temperatures for each location are extrapolated from the NASA average daily maximum and minimum temperatures for each month of the year using Equation 6. This assumes that the minimum temperature occurs 03:00-04:00, and the maximum temperature occurs 15:00-16:00.

Equation 6: Calculation to create hourly external temperatures.

$$hTemp_h = \left(\frac{TdMax_m - TdMin_m}{2}\right)\left(-\sin\left(2\pi\left(\frac{h+2}{24}\right)\right)\right)$$

Where;

$hTemp_h$	(°C)	=	External temperature at hour h
h		=	Hour of the day
$TdMax_m$	(°C)	=	Average daily maximum external temperature for month m
$TdMin_m$	(°C)	=	Average daily minimum external temperature for month m
m		=	Month of the year, 1 = Jan; 2 = Feb;…Dec = 12

The hourly external temperatures, along with the thermal properties of the building envelope and any internal heat gains, are used to determine heating demand on an hourly, and annual, basis. The hourly external temperatures are also used to determine the mean annual temperature for each location.

The sinusoidal temperature profiles for the different locations in Table 23, derived from the NASA weather data using Equation 6, were used as inputs to model an example SBM dwelling, as described in Figure 45. The resulting heating requirements were compared with those generated when hourly observed (IWEC or TMY3) temperature data was used as an input instead (see Table 50 and Figure 46). Where observed weather files for the original locations were not available, weather files for nearby locations were used instead.

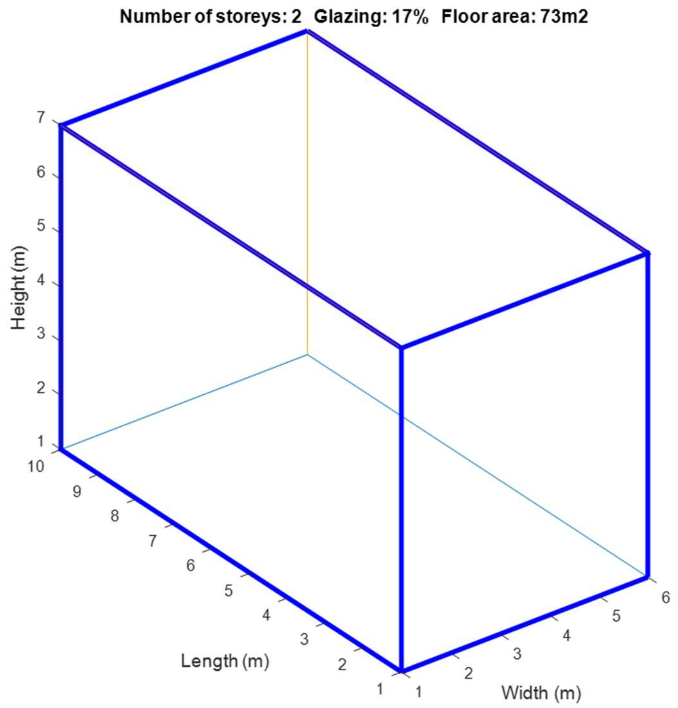


Figure 45: Schematic of an example SBM dwelling. The dwelling is of brick and block construction with an average envelope U-value of 0.3 Wh/m^{2}K and an infiltration rate of 0.7 air changes per hour. Occupant density is 35m^2/person.

Table 50: Comparison of heating demands resulting from NASA daily maximum and minimum temperature data, and hourly observed weather data for different locations.

Location	NASA data input (based on daily maximum and minimum)		Observed weather data input (hourly)			
	Mean annual temp. (degrees C)	Annual heating required (kWh/m2)	Alternative location	Weather data file type	Mean annual temp. (degrees C)	Annual heating required (kWh/m2)
Oslo	4.8	99.0	n/a	IWEC	6.6	81.4
Seattle	8.7	52.9	n/a	TMY3	11.8	23.3
Carcassonne	12.8	26.9	Montpellier	IWEC	14.8	15.9
Melbourne	14.5	14.3	n/a	RMY	15.0	7.4
Athens	18.5	4.0	n/a	IWEC	17.9	4.9
Macapa	25.8	0	Belem	IWEC	26.5	0
Mumbai	26.6	0	n/a	IWEC	27.0	0

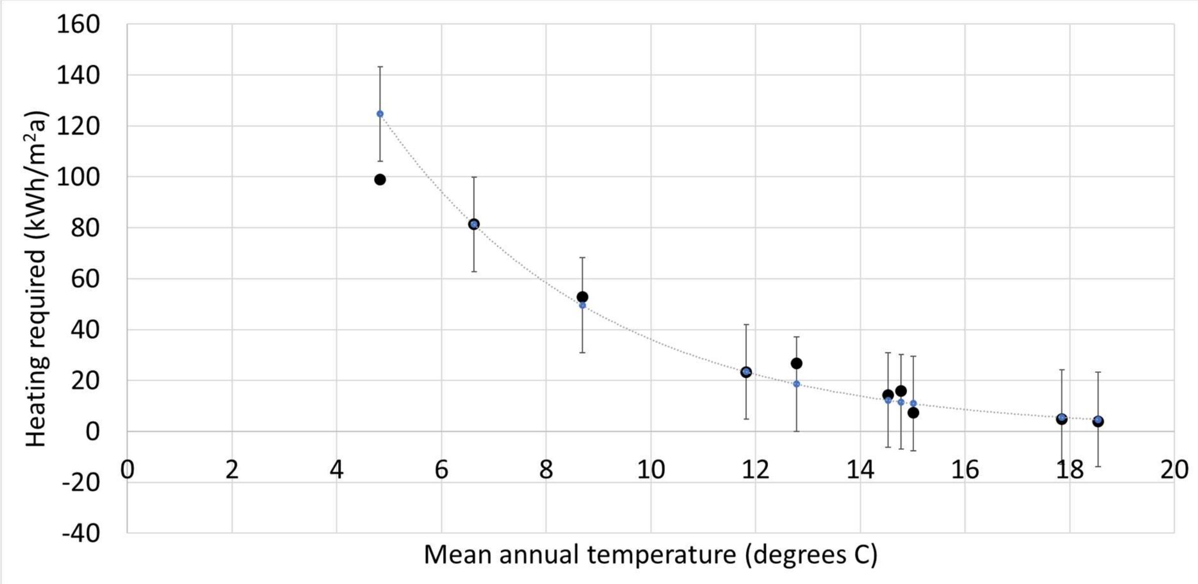


Figure 46: Graph showing the relationship between mean annual temperature and heating required for the example SBM dwelling (Figure 45) for all the locations and temperature inputs in Table 50. Error bars show two standard deviations from the trendline (18.5 kWh/m^{2}a). All results, but one, are within this margin of error. The NASA result for Oslo is 2.8 standard deviations from the trendline.

Figure 46 demonstrates a consistent relationship exists within SBM between mean annual temperature and heating required regardless of the type of weather data input (daily maximum/minimum satellite-based NASA, or hourly surface observation-based). Table 50 demonstrates that different mean annual temperatures may be measured/reported for the same location depending on the weather data source.

7.6.3. PV generation

In SBM hourly insolation levels incident on an optimally-tilted equator-facing surface are extrapolated from the NASA three-hourly average insolation levels for each month of the year (see Section 7.5). This data was used as inputs in modelling the example SBM dwelling (Figure 45). The resulting PV generation outputs were compared with those generated when hourly observed (IWEC or TMY) insolation data was used as an input instead (see Table 51 and Figure 47). Where observed weather files for the original locations were not available, weather files for nearby locations were used instead.

Table 51: Comparison of PV generation resulting from NASA three-hourly insolation data, and hourly observed weather data for different locations.

Location	**NASA data input (based on three-hourly insolation data)**		**Observed weather data input (hourly)**			
	Mean hourly input (Wh/m^2)	Annual PV gen. (kWh)	Alternative location	Weather data file type	Mean hourly input (Wh/m^2)	Annual PV gen. (kWh)
Oslo	123	4,568	n/a	IWEC	79	3,000
Seattle	145	5,450	n/a	TMY3	135	5,053
Carcassonne	165	6,127	Montpellier	IWEC	150	5,624
Gatwick	110	4,165	n/a	IWEC	80	3,219
Athens	198	7,228	n/a	IWEC	173	6,502
Macapa	195	7,188	Belem	IWEC	116	4,319
Mumbai	252	9,227	n/a	IWEC	146	5,554

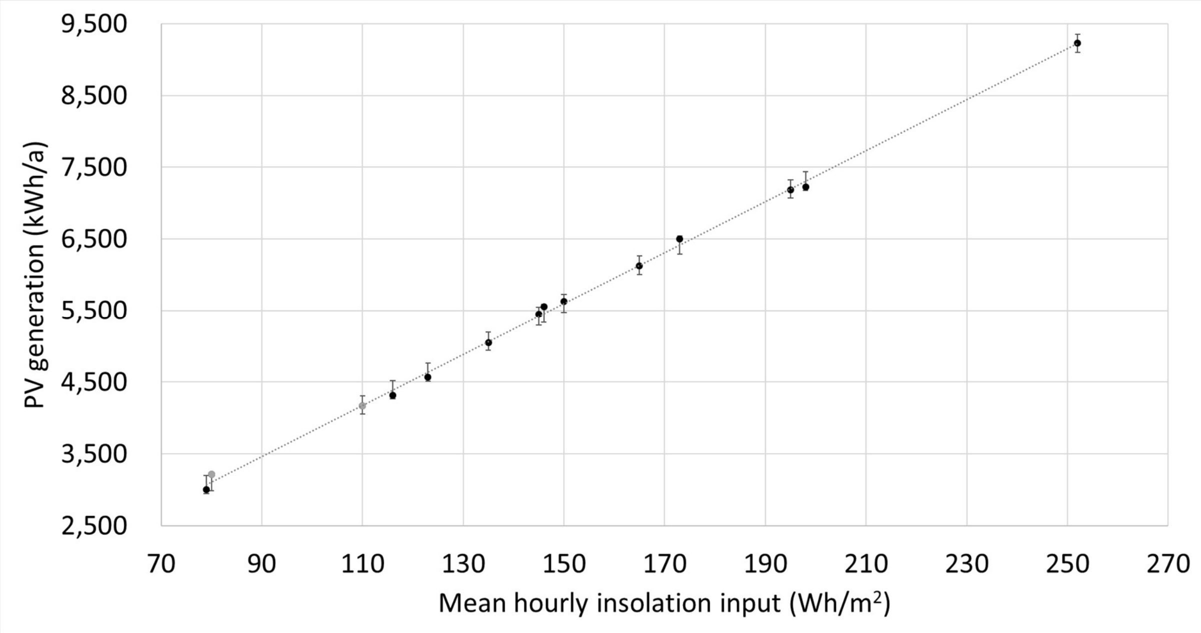


Figure 47: Graph showing the relationship between mean hourly insolation inputs and resulting annual PV generation for the example SBM dwelling (Figure 45) for all the locations and insolation inputs in Table 51. Error bars show two standard deviations from the trendline (127 kWh/a). All results are within this margin of error.

Figure 47 demonstrates that, regardless of the type of weather data input (three-hourly, satellite-based NASA, or hourly surface observation-based), SBM PV generation output is a function of the level of insolation exposure. Table 51 demonstrates that different levels of insolation may be measured/reported for the same location depending on the weather data source.

7.6.4. Embodied carbon and energy

SBM uses the process method for embodied carbon and energy calculations (see Section 5.3). Similarly, the Domestic Building Model (DBM) developed by Hammond and Jones (Hammond & Jones, 2009) uses the process method and the Inventory of Carbon and Energy (ICE) database to determine estimates of embodied carbon (EC) and embodied energy (EE), with a reported uncertainty of ±30%. Table 52 and Figure 48 show a comparison between the example 100m^2 semi-detached dwelling described in Hammond and Jones, and a brick and block (with no carbon sequestration assumed) dwelling of approximately the same size modelled in SBM. Not all the building elements addressed in DBM are also addressed in SBM.

Table 52: Comparison of embodied results from DBM and SBM for different building elements in similar 100m^2 semi-detached dwellings.

	Embodied carbon ($kgCO_2/m^2_{element}$)		**Embodied energy ($kWh/m^2_{element}$)**	
Building element	DBM estimate	SBM estimate	DBM estimate	SBM estimate (converted to primary energy)
Ground floor	86	70	217	255
Upper floor	23	34	126	64
Roof	37	28	154	139
Internal wall	26	27	81	211
uPVC window	112	174	639	953
External wall	64	67	217	273
Foundations	103	n/a	241	n/a
Party wall	45	n/a	134	n/a
Misc. (per m^2 floor area)	25	n/a	97	n/a
Waste (per m^2 floor area)	76	n/a	333	n/a

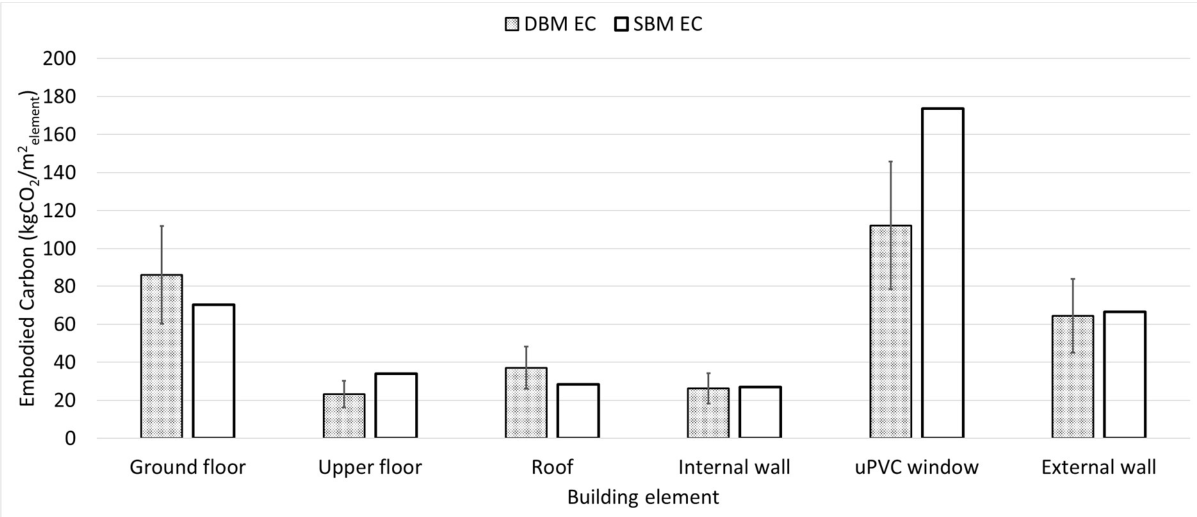


Figure 48: Comparison of embodied carbon results from DBM and SBM. Building elements that are not addressed in SBM are not shown. Error bars show the 30% uncertainty reported for DBM results.

Figure 48 shows that, for both DBM and SBM modelled buildings, the windows are the most carbon intensive elements of the buildings. However, the overall contribution of the different elements to the total embodied carbon of the building depend on the size of the elements. For example, Figure 49 shows that, for the same semi-detached building specification, modelled in SBM, the external walls are a larger contributor to the overall embodied carbon value. This is because there is more surface area of external wall than there is of window.

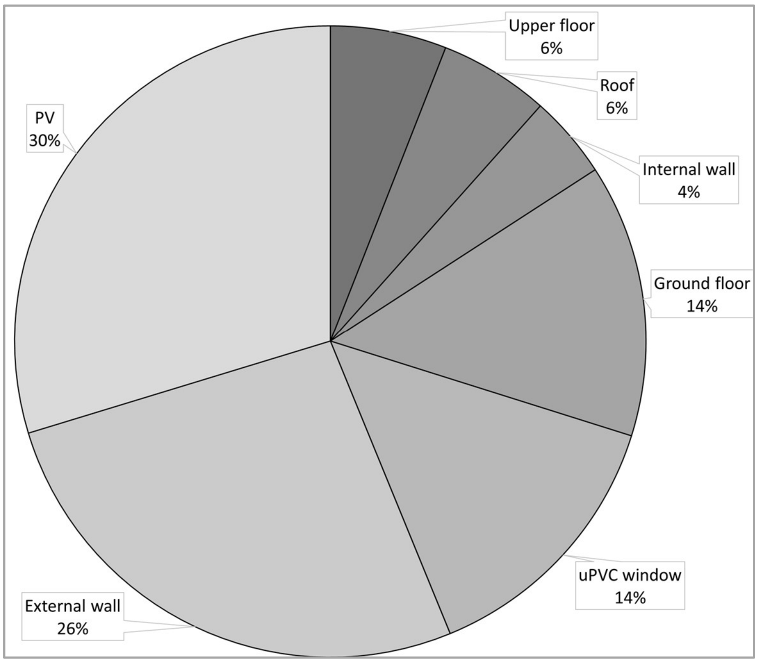


Figure 49: Contribution of building elements in two 100m^2 semi-detached two-storey dwellings to the overall embodied carbon of the buildings modelled in SBM. As these buildings were modelled in SBM, a roof-mounted PV array is also included in the embodied carbon calculations.

Hammond and Jones (Hammond & Jones, 2009) also provide benchmark embodied metrics for different types of dwelling. Table 53 and Figure 50 show a comparison of the embodied metrics reported in Hammond and Jones (Hammond & Jones, 2009) and those calculated in SBM for different types of dwelling.

Table 53: Comparison of DBM and SBM embodied results for different types of dwelling. For this comparison PV has been excluded from the SBM calculations. Embodied metric estimates, to cover the extra elements included in the DBM calculations (foundations, party walls, miscellaneous and waste), are included in the SBM results. Building types are ordered by DBM embodied carbon estimate.

	Typical newly built English dwellings		**Embodied carbon ($kgCO_2/m^2$)**		**Embodied energy – primary (kWh/m^2)**	
Building type	Percentage of new properties	Average floor area (m2)	DBM estimate	SBM estimate	DBM estimate	SBM estimate
Bungalow (detached)	11	76	618	429	2,266	3,139
Apartment (three-storey)	24	50	480	373	1,833	2,831
Apartment (four-storey)	24	50	460	375	1,750	2,891
Semi-detached	15	73	425	358	1,560	2,718
Detached	31	125	408	355	1,993	2,640
Terraced	20	68	368	337	1,348	2,654

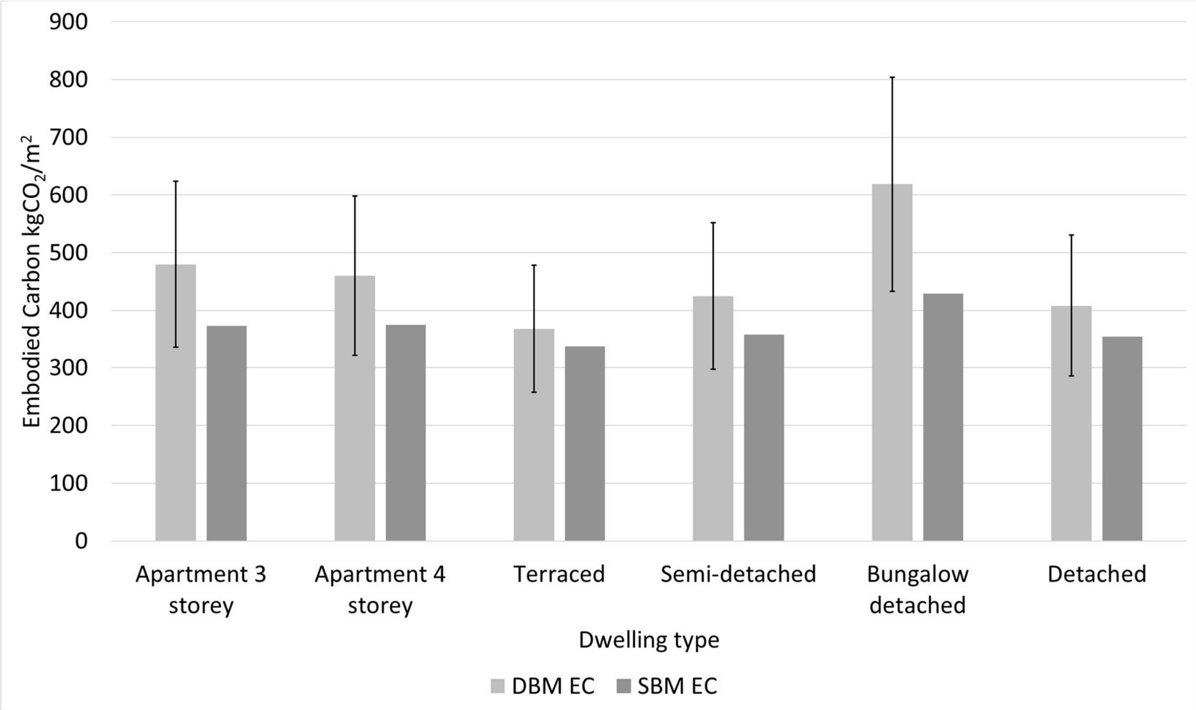


Figure 50: Comparison of embodied carbon results from DBM and SBM for different dwelling types. Error bars show the 30% uncertainty reported for DBM results.

Figure 48 and Figure 50 demonstrate that SBM produces similar embodied carbon outputs when compared with the Domestic Building Model (DBM). It is evident from Figure 49 that the embodied carbon associated with windows is a significant contributor to the dwellings' overall embodied carbon content, and that this is the building element for which the greatest difference between SBM and DBM is apparent (Figure 48). However, it should be noted that, in SBM, PV contributes twice as much to the dwelling embodied carbon content compared to the windows (see Figure 49). DBM does not consider PV.

7.6.5. Modelling a real building in SBM

SBM balances energy demand from heating and electricity against electricity that can be generated by a roof-mounted PV array. As described in Chapter 3, the school in Exeter, Montgomery Primary School, was designed to be net zero energy in use based on a similar concept (Parkin, et al., 2015). The school has a roof-mounted PV array sized to generate annual electricity output at least equal to the annual electricity demand of the school (Mitchell, 2014). In addition, the Passivhaus design concept was incorporated into the building design to minimise heat energy demand.

The performance of Montgomery Primary School was monitored after the completion of the building using readings from the import/export electricity meter on the grid supply, and the generation meter on the PV system (Mitchell, 2014). There is no gas connection to the school, so all energy demand data relates to electricity demand, and includes space heating, water heating and cooking. The performance report notes that electricity consumption is not strongly correlated with variations in external temperature, suggesting that space heating demand does not have a significant influence on the school's overall electricity consumption. This should be expected given the employment of the Passivhaus design concept for the purpose of minimising space heating demand, and agrees with the findings in (Monahan & Powell, 2011) that as thermal envelopes (in the UK) become more efficient, energy demand is increasingly associated with end uses other than heating.

The data provided in the Montgomery Primary School performance report has been used for comparison with outputs from an SBM building with a similar design specification (see Figure 51 - construction element details are in Appendix A56). For this comparison, SBM input values for occupancy density (6.2 m^2/person) and electricity demand (350 kWh/person per year, not including heating) are based on values provided in the school performance report. In addition, the occupancy profile (and resulting heat gains) used for this model reflects the pattern of usage associated with school buildings (occupied during week days and empty at weekends). Table 54 shows a comparison of Montgomery Primary School measured performance and equivalent SBM outputs.

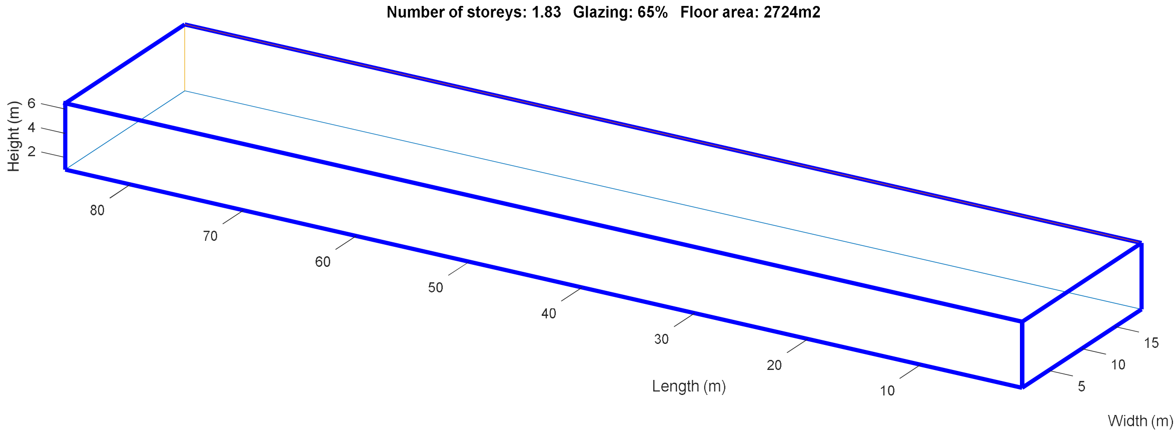


Figure 51: Schematic of Montgomery Primary School modelled in SBM. The roof-mounted PV array is modelled as tilted at 35º to the horizontal. In order to accommodate the 165 kWp PV array the real school building is wedge-shaped (see Figure 17), with a first floor smaller than the ground floor. This design is modelled in SBM as a school with 1.83 storeys.

Table 54: Comparison of annualised Montgomery School reported performance and Montgomery School SBM outputs.

SBM component	Montgomery School reported	Montgomery School in SBM	Notes
Heating set point (ºC)	Not specified.	20	Passivhaus specifies 20 ºC
Space heating demand (kWh/m^{2}a)	Not specified.	1.03	Measured data suggests space heating demand is minimal.
Electricity demand (kWh/a)	166,022	162,875	159,199 kWh measured demand during period 23/09/2013 – 08/09/2014
Electricity generated (kWh/a)	187,793	180,147	514 kWh average daily generation based on measurements during period 23/09/2013 – 08/09/2014. The monitoring report notes that the 2014 summer was significantly sunnier than average.
Electricity exported (kWh/a)	Not specified.	93,679	
Electricity imported (kWh/a)	90,150	76,406	Measured imported electricity reported as 54.3% of demand. SBM balance resolution is hourly. Demand-generation imbalances on shorter timescales (as in the measured data) are not calculated.
Net electricity exported (kWh/a)	21,764	17,273	20,870 kWh net export of electricity reported during period 23/09/2013 – 08/09/2014
Generated and used on site (kWh/a) (demand – import)	75,872	86,469	SBM balance resolution is hourly. Demand-generation imbalances on shorter timescales (as in the measured data) are not calculated.

Figure 52, Figure 53, Figure 54 and Figure 55 show the SBM hourly profiles for electricity demand, PV generation, exported electricity and imported electricity respectively.

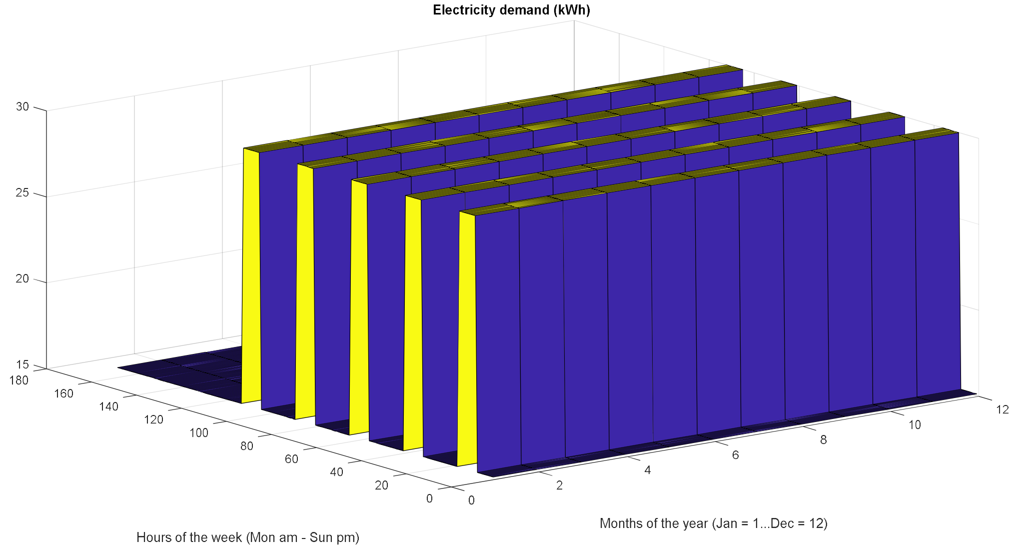


Figure 52: SBM electricity demand profile for Montgomery Primary School. Demand is assumed to peak during the school day. A constant based load is assumed at all other times.

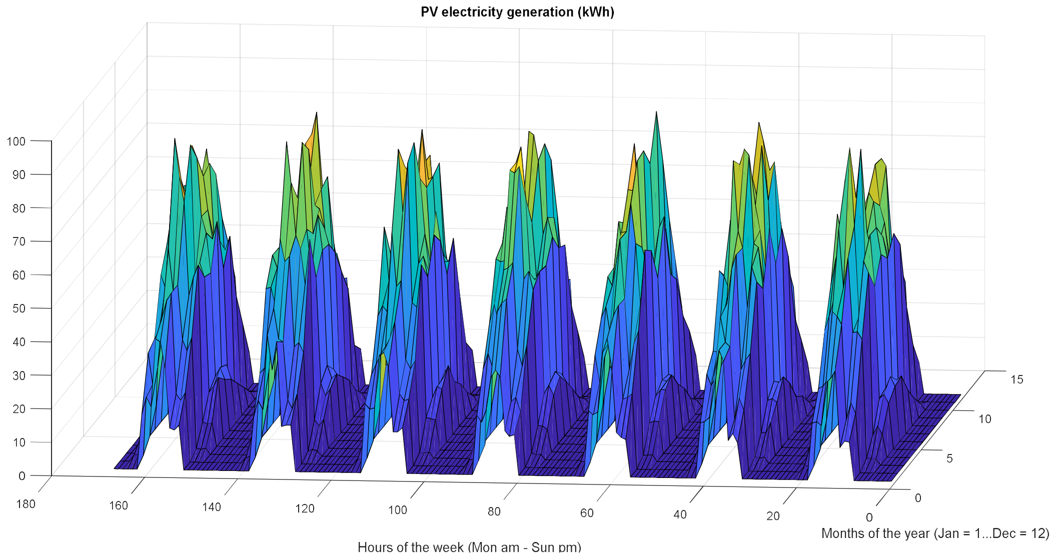


Figure 53: SBM PV generation profile for Montgomery Primary School.

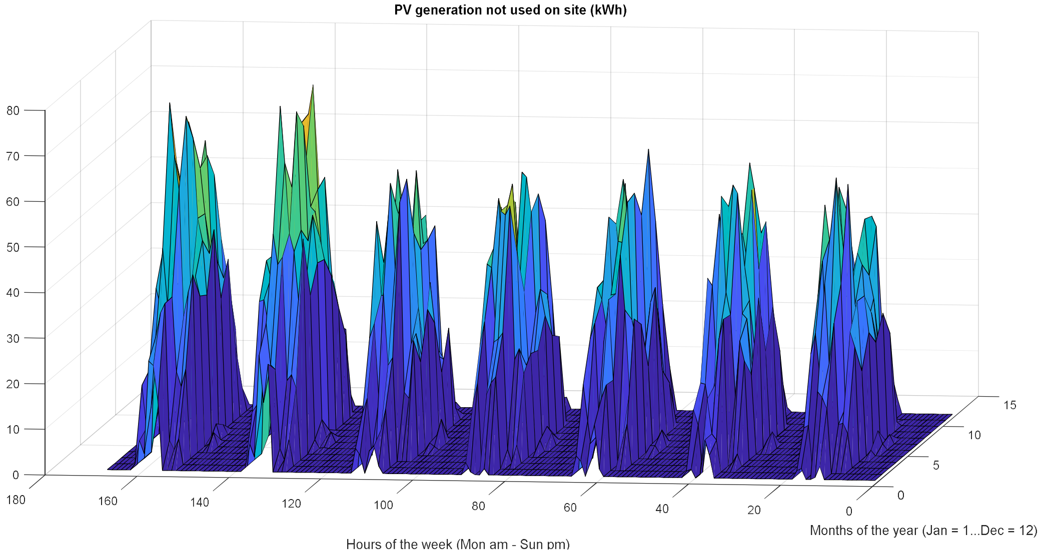


Figure 54: SBM profile for PV electricity generated in excess of demand at Montgomery Primary School, and therefore exported. Excess generation is greater at the weekends when it is assumed the school is not occupied.

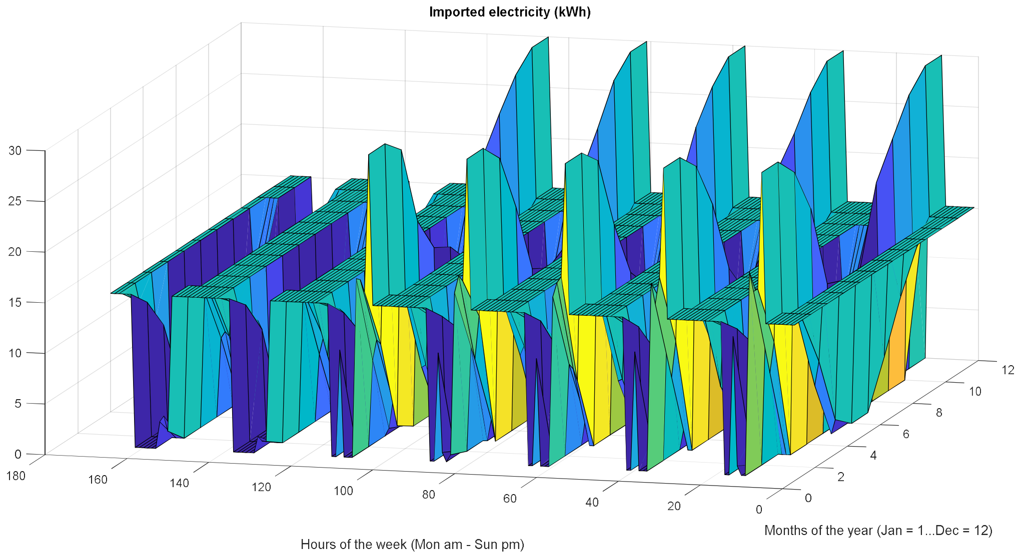


Figure 55: SBM profile for imported electricity, when demand exceeds PV generation. Electricity imports rise during the winter months at the beginning and end of the school day when the school is occupied, but PV generation is limited.

7.7. SBM data analysis methodology

The Standard Building Model (SBM) is a predictive calculation method. The result of each SBM calculation is a continuous variable describing the net carbon emissions, or energy demand, of a building system object with 14 specified feature characteristics. While the SBM objects are designed to represent real buildings, it is acknowledged that the level of detail (or number of features) required to describe a real building is far greater than the capacity of SBM. For this reason, analysis of the SBM generated data focused on how the population of SBM objects perform in comparison with each other, responding to their assigned feature characteristics, rather than how each object performed as an individual unit. A normative approach was taken to analysis of the SBM data, and each SBM object was classified as achieving, or not, the ZCB or ZEB goal.

It was recognised that attempting to look at trends, or optimum solutions, associated with carbon emissions, or energy demand, magnitudes could be misleading given the SBM objects are not detailed building models. In addition, the concept of the curse of dimensionality indicates that as the number of dimensions (i.e. features) of a problem increase, it is ever more difficult to find a real optimum in the high-dimensional space. This is because as the number of dimensions of a particular problem grow, so the data necessary to comprehensively describe the problem grows exponentially. Rather than trying to identify which combination of feature characteristics would produce the optimum SBM building system object, this research was interested in identifying which features played the greatest roles in shaping the populations of SBM objects that achieved, or didn't achieve, the ZCB or ZEB goal.

SBM generated 24.7 million cases. The characteristics of each case are a result of the combination of 14 different case input variables as detailed in Table 55. For each case, the interaction of the input variables resulted in a net carbon emissions (kgCO_2e), and a net energy demand (kWh), output value, normalised to the internal floor area. Defined aspect ratios (see Table 42) were used to identify and remove unrealistically narrow and tall building system objects from the dataset. The overall result was two 24.7 million x 15 matrices in which the first 14 columns identified the input variables and the last column was either the carbon, or the energy, output. Cases where the output carbon or energy value was less than, or equal to, zero were classified as zero carbon buildings (ZCBs) and/or zero energy buildings (ZEBs) respectively. Classification trees were used to identify patterns in the ZCB and ZEB populations associated with the different features. The result of this was a presentation of knowledge of the data in the form of logical structures, rather than quantitative SBM calculation outputs that could be further interrogated using sensitivity analysis.

Table 55: SBM case code units, characteristics and values.

Case code unit	Input variable (Classification tree feature)	Case characteristic	Case code unit value
1	Building location	Athens	1
		Carcassonne	2
		Macapa	3
		Mumbai	4
		Oslo	5
		Seattle	6
2	Construction material	Brick	1
		Straw (including sequestration)	2
		Straw (excluding sequestration)	3
3	Calculation boundary	Operational only	1
		Operational + Embodied	2
4	Balance period	Annual	1
		Monthly	2
5	PV location	Onsite	1
		Remote	2
6	Infiltration level (air changes per hour at normal pressure)	0.042 + MVHR	1
		0.700	2
		0.343	3
7	Occupancy density	No occupants	1
		35 m^2/person	2
		20 m^2/person	3
8	PV specification	Low embodied metrics	1
		High embodied metrics	2
9	Glazing U-value (W/m^2K)	1.4, 0.8, 0.68	As case label
10	Wall U-value (W/m^2K)	0.10 – 0.18	As case label
11	Glazing %	10 - 80	As case label
12	Number of storeys	1 - 32	As case label
13	Width (m)	Calculated value (see Table 42)	As case label
14	Footprint (m^2)	45 – 450	As case label

The populations of ZCBs and ZEBs within the overall population of cases were analysed using a classification tree algorithm in MATLAB and separately using odds ratios and logistic regression.

As an example of SBM inputs and outputs, Table 56 describes one SBM case which results in a net annualised carbon emissions value of -27 $kgCO_2e$, and a net annualised energy demand of 255 kWh, per m^2 internal floor area. This result is for a four-storey building in Oslo with 80% glazing (see Figure 56). The PV array is 45 m^2 (the same size as the roof –

and footprint) and is located remotely in Accra. This example SBM case is classed as a Zero Carbon Building (ZCB), but not as a Zero Energy Building (ZEB).

Table 56: The features of the SBM case identified by the unique case code 5/2/2/2/2/2/1/2/1.4/0.1747/80/4/7.5/45

Case code unit	Input variable (Classification tree feature)	Case characteristic	Case code unit value
1	Building location	Oslo	5
2	Construction material	Straw (including sequestration)	2
3	Calculation boundary	Operational + Embodied	2
4	Balance period	Monthly	2
5	PV location	Remote	2
6	Infiltration level (air changes per hour at normal pressure	0.700	2
7	Occupancy density	No occupants	1
8	PV specification	High embodied metrics	2
9	Glazing U-value (W/m^2K)	1.4, 0.8, 0.68	1.4
10	Wall U-value (W/m^2K)	0.10 – 0.18	0.1747
11	Glazing %	10 - 80	80
12	Number of storeys	1 - 32	4
13	Width (m)	Calculated value (see Table 42)	7.5
14	Footprint (m^2)	45 – 450	45

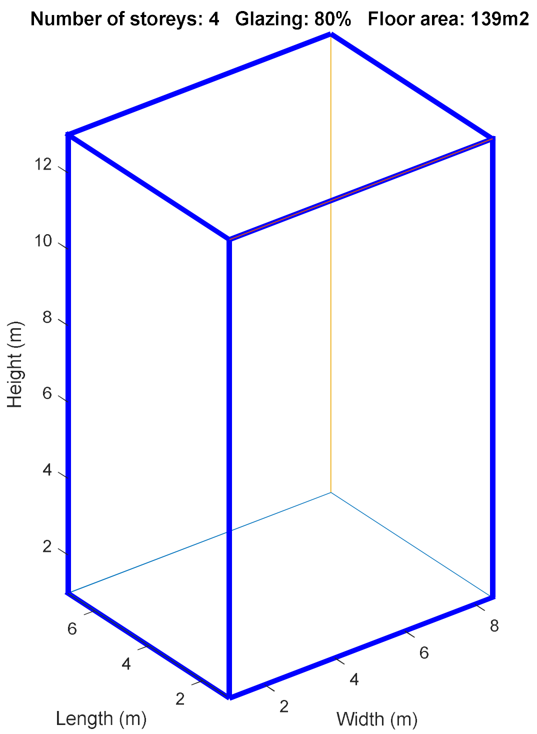


Figure 56: Schematic of the example SBM case described in Table 56.

7.7.1. Classification trees

Classification tree uses recursive partitioning to split data into ever smaller subsets of similar classes (Lantz, 2013). Classification trees are based on input variables (or features) X, and the output Y. In this research, the features in Table 55 are the inputs X. The output Y is the SBM case class (zero, or non-zero).

The MATLAB function *fitctree(X,Y)* returns a binary classification tree where each branching node is split based on the features X. The classification tree splits nodes based on the Gini Diversity Index measure of node impurity (see Equation 7).

Equation 7

$$Gini\ Diversity\ Index = 1 - \sum_{i=1}^{c} p_i^2$$

c = number of class levels (in this case, two – zero or non-zero)

p_i = proportion of outputs at that node falling into class level i

Beginning at the root node the, algorithm selects the feature that is most predictive of the target class (ZCB or ZEB). The population is then split into subsets based on the feature values. This results in the first set of tree branches.

The algorithm continues to further split the nodes, based on the most predictive feature at that node, until a stopping criterion is reached. This occurs at a node if:

All (or nearly all) of the outputs fall into the same class; a pure node (Gini Diversity Index = 0)

There are no remaining features to distinguish among outputs

The minimum leaf node size is reached (for this research 500,000 or fewer unless otherwise specified).

7.7.2. Odds ratios and logistic regression

The odds ratio (OR) is the ratio of the odds of an event occurring in one group to the odds of it occurring in another group. If the odds of a ZCB in each of the groups are $Odds_1(ZCB)$ (the first group) and $Odds_2(ZCB)$ (the second group), then the odds ratio is given by Equation 8.

Equation 8

$$OR = \frac{Odds_1(ZCB)}{Odds_2(ZCB)}$$

OR = 1	A ZCB is equally likely to occur in both groups
OR > 1	A ZCB is more likely to occur in the first group
OR < 1	A ZCB is more likely to occur in the second group

Where

$$Odds(ZCB) = \frac{P(ZCB)}{1 - P(ZCB)}$$

And

$$P(ZCB) = \frac{Number\ of\ ZCBs\ in\ the\ population}{Number\ of\ cases\ in\ the\ population}$$

Logistic regression can be used to identify a relationship between a binary outcome variable (e.g. occurrence of a ZCB) and a predictor variable (e.g. average annual temperature).

Equation 9

$$Logit(ZCB) = Log_n(Odds(ZCB))$$

The logit transformation maps probabilities, ranging from 0 to 1, to log odds, ranging from negative infinity to positive infinity, which can be plotted against predictor variables.

Chapter 8. Conclusions and further work

Global climate change is driven by greenhouses gases, predominantly carbon emissions. There are many different building system conceptual frameworks implemented around the world which aim to reduce the contribution of buildings to climate change. However, most such frameworks focus on reducing energy demand.

This work demonstrates that the design features leading to a zero energy building are not necessarily the same as those leading to a zero carbon building. In either case, limitations imposed to achieve the zero goal may not be appropriate, or applicable, in all global locations.

In this PhD a conceptual framework was developed which describes a building as a system of interacting components, including:

- The properties of the building itself (thermal envelope characteristics and embodied carbon/energy properties);
- Building energy demand profiles (heating and cooling, and occupants' use of plug-in appliances); and
- On- and off-site PV energy generation profiles (and the associated offset of carbon emissions from energy demand).

The components of the conceptual framework formed the basis for building a Standard Building Model (SBM) in MATLAB with variable parameters such as building dimensions, occupant density, environmental conditions and energy grid carbon intensities (CIs). The outcomes of building system component interactions were assessed both including and excluding embodied carbon/energy, and with regard to net carbon and energy balances measured on both annual and monthly scales. The outcome assessments resulted in cases defined as Zero Carbon Buildings (ZCBs), Zero Energy Buildings (ZEBs), both or neither.

SBM was used to simulate 24.7 million cases covering six global locations. This created a design space for all cases bounded by the limits of the building system feature variables. By constraining the variable limits further design spaces were identified within which only ZCBs and ZEBs exist. Across all locations, it was found that the design space within which ZCBs exist is nearly twice the size of that within which ZEBs exist. This is not a surprising result as the carbon sequestration properties of the straw-walled SBM building system objects allow for more offsetting of carbon emissions than is the case for energy demand. However, this does demonstrate that focusing on energy demand takes a narrower approach to addressing the problem of climate change, and there are valid building design solutions that are not visible if carbon emissions are not included in the metric of measurement.

The most important feature determining the size of the design space for both ZCBs and ZEBs globally was building height (i.e. the ratio of PV generation area to internal floor area). This was also found to be true at the individual location level. However, the characteristics of different locations determined the further features of importance. It was found that the characteristics of locations' electricity grids (i.e. electricity CIs) are better predictors of the size of the ZCB design space than are the locations' environmental characteristics (i.e. mean annual temperatures).

This thesis has identified the potential for the importance of the features within a zero-carbon framework to change with time. The carbon intensity of local electricity grids have been demonstrated to have a significant impact on what building system features are important in the design of a zero building. It is a global intention that the carbon intensities of electricity (and other energy) grids will reduce with time, and so design features that are beneficial in the design of zero carbon buildings have the potential to change with time too.

For example, a 2011 UK study comparing different design approaches (including ground source heat pumps, thermal solar and photovoltaics) in new low-energy homes concluded that ground source heat pumps had the highest carbon emission rate over a projected 20-year period (Monahan & Powell, 2011). The study assumed that the UK electricity grid CI would fall from 0.53 $kgCO_2/kWh$ to 0.37 $kgCO_2/kWh$ over the period in question. However, the UK electricity carbon intensity fell to 0.265 $kgCO_2/kWh$ in 2017 and the UK Committee on Climate Change is now recommending heat pumps as a route to reducing carbon emissions from homes (Committee on Climate Change, 2018b; Committee on Climate Change, 2018c).

8.1. Further work

This work indicates that the significance of embodied carbon in a building is far outweighed by the importance of the balance between operational carbon emissions and any carbon offset from PV electricity generation. However, the current design of the Standard Building Model calculates embodied carbon using the bottom-up process method. As discussed in Section 5.3, this calculation methodology may underestimate the true level of carbon emissions associated with the manufacture of materials and products.

The application of the input-output calculation technique to the Standard Building Model may provide a different perspective on the importance of embodied carbon. This would require additional information about the financial costs of the materials and products incorporated into the buildings (for example, from a bill of quantities), along with knowledge of the economic sector (and country) in which they are produced. The further inclusion of information about planned costs and actual costs (from a real construction project) would also provide some information on the embodied carbon costs of the waste streams from building projects – i.e. materials/products purchased for a building that never end up as part of the building, but still add to its overall carbon cost.

It is evident that there is a financial cost associated with carbon emissions and their impact on climate change, and work is being undertaken to formalise a 'cost of carbon' (Department for Business, Energy & Industrial Stratey, 2016; Watkiss, 2006). The incorporation of financial information, and its links to carbon emissions, into the Standard Building Model would also allow for comparisons between the cost of producing buildings and the net potential rewards from zero carbon designs, assuming a globally implemented cost of carbon. For example, building designers could ask questions such as: Is it better value for money to invest in PV, for a particular building project, or to build with straw bales?

8.2. Postscript

This PhD work has developed a new conceptual framework to describe global building systems that combine building design specification and ZeroCC building standard requirements. The new framework includes components that are often disregarded or simplified in more established low and zero energy/carbon building frameworks, for example, occupant energy demand (plug loads), embodied carbon/energy and energy grid characteristics. Interrogation of this framework has identified the importance of electricity grid carbon intensities in not only determining the size of zero carbon building design spaces, but also the identification of key features for the design of zero carbon buildings. It has also identified that the global design space within which zero carbon buildings exist is different to that within which zero energy buildings exist. These factors are important to appreciate for the global construction industry to reduce its share of carbon emissions. This research demonstrates that features promoted in zero energy building designs will not necessarily result in the reduced carbon emissions assumed. In addition, with the changing characteristics of global electricity grids, features promoted in the zero carbon building designs of today will not necessarily continue to produce the carbon emissions reductions envisaged into the future.

8.3. Epilogue

During the viva voce examination of this thesis, the wider context within which this work sits was considered. The following discussion covers a number of the issues raised, and provides a wider view of the subject of climate change and the construction industry.

Four decades ago, an investigation into the implications of increasing levels of carbon dioxide in the atmosphere outlined far reaching concerns about the future of the planet:

> *Life on our own earth is possible only because of its equable climate... We now have incontrovertible evidence that the atmosphere is indeed changing and that we ourselves contribute to that change. Atmospheric concentrations of carbon dioxide are steadily increasing, and these changes are linked with man's use of fossil fuels and exploitation of the land… If carbon dioxide continues to increase, the study group finds no reason to doubt that climate change will result and no reason to believe that these changes will be negligible.*

(National Research Council, 1979)

Since then carbon dioxide (CO_2) emissions have risen steadily (see Figure 1 in the Introduction). At the same time, the relationship between CO_2 emissions and global warming has become much better understood. The 2018 Intergovernmental Panel on Climate Change (IPCC) special report on global warming (IPCC, 2018) estimates that human activities have already caused approximately 1.0°C of global warming above pre-industrial levels, and presents future scenarios that are predicted to result from continued anthropogenic carbon dioxide emissions:

> *Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C…Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems[1].*

(IPCC, 2018)

The goal of limiting global warming to 2°C or below is necessarily clear and simple, and has now been ratified in the United Nations' 2015 Paris Agreement (United Nations, 2015). However, what is needed to reach that goal, and the consequences of failure, are more complicated. It is likely that the rapid and far reaching transitions are possible, but they will require commitments from governments, industry and populations together, probably at a financial cost. At the same time, global populations are expected to increase (see Figure 11 in Chapter 2), requiring more economic output, which is itself closely linked with CO_2 emissions (IPCC, 2014). On top of this, the motivation to undertake the far reaching transitions is not internationally uniform. Although the consequences of global warming are already becoming apparent, they are not felt equally across the planet. For example, extreme weather events tend to be devastating for local populations, and suffering is frequently more severe in developing regions.

The idea of low and zero carbon and energy buildings (i.e. ZeroCC buildings) has developed because it is acknowledge that the construction industry, and the products it produces, are responsible for significant CO_2 emissions (IPCC, 2014). It is therefore is logical, and morally appropriate, that the global construction industry should, where is has the power to do so, implement those far-reaching transitions that are needed. However, the construction industry itself faces its own challenges in this regard. Fostering intent to do something is

[1]In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030, reaching net zero around 2050. For limiting global warming to below 2°C CO_2 emissions are projected to decline by about 25% by 2030 in most pathways and reach net zero around 2070.

one part of the solution, but it is also necessary to ensure that what is done results in transitions leading to real reductions in CO_2 emissions, not just buildings that pass a ZeroCC 'test'.

As discussed in Chapter 2, there are many ZeroCC frameworks implemented around the world that have been developed to drive improvements in the performance of buildings. Some are compulsory, existing within national and international legislation, for example, UK Building Regulations and the European Union Energy Performance of Buildings Directive. In these cases, governments have taken the initiative to drive the improvements, but often with a secondary view on what is achievable and financially viable for their national industries (for example, see the argument put forward in the Infrastructure Bill debate at the end of Section 4.2). Others are voluntary, working within certification schemes and providing aspirational benchmarks, for example the Passivhaus certification scheme and the Living Building Challenge. These frameworks demonstrate what is possible, and further the discussion on what far-reaching transitions in the construction industry might look like. In general, the purpose of all these frameworks is to encourage changes in the way buildings are designed and constructed.

The design of the ZeroCC frameworks themselves often reflect concerns relevant to particular times and locations, and what constitutes acceptable performance varies. The Passivhaus framework, designed to address the challenge of reducing heat loss in houses that are subject to the German winter, involves stringent airtightness requirements (far more so than UK Building Regulations). In the UK, legislation has gradually reduced the acceptable U-values (heat transmission coefficients) of building components over time (see Figure 57). UK Building Regulations were strengthened in response to the 1973 oil crisis before climate change had become a widely accepted concern (meaning that the ZeroCC label was not really applicable at the time). However, the improvements were designed to reduce energy demand, and were therefore also beneficial from a climate change perspective.

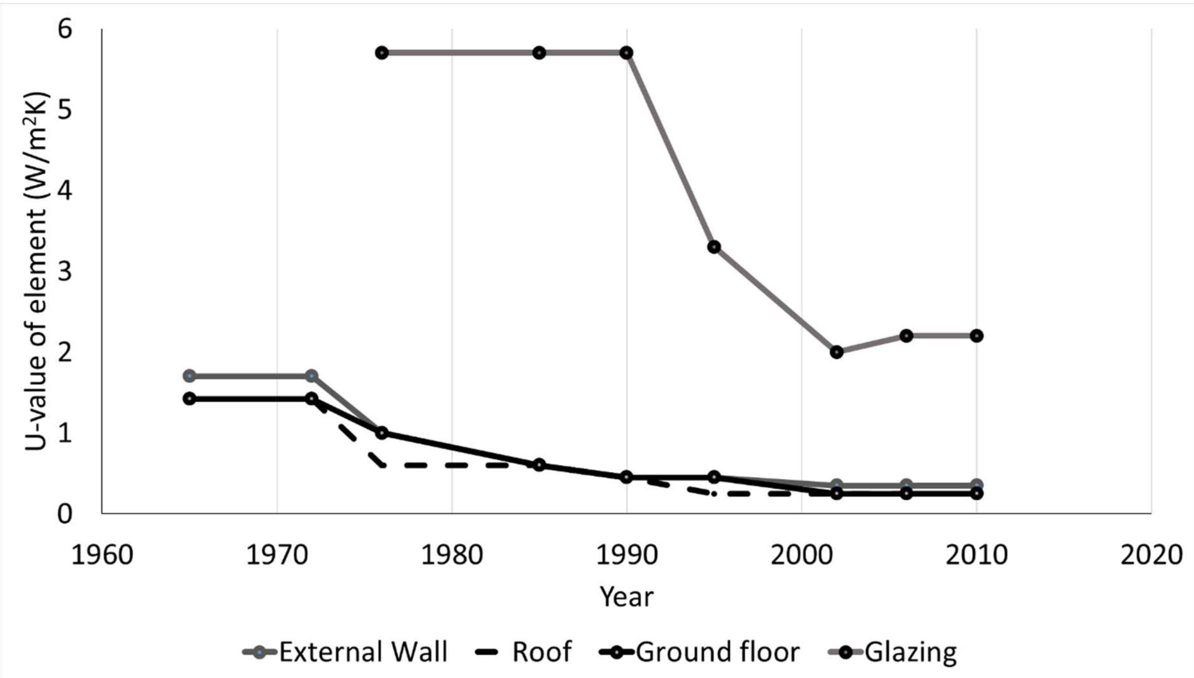


Figure 57: Reduction in maximum U-values for different building elements as required by revisions of UK Building Regulations. Data from (Korolija, et al., 2013).

While these frameworks have driven changes in the construction industry with regard to the design of buildings, the frameworks are usually applied at the design stage, and it has been found that the performance of buildings as constructed often does not live up to expectations. For example, a US review of building energy requirements found that limited account is taken of the effect of occupant behaviour, or building management, on energy use over time leading to the potential for discrepancies between proposed and measured performance of new buildings (see Figure 58). Figure 14 in Chapter 3 also demonstrates that even in Passivhaus certified buildings, in which the design of thermal envelope properties is carefully scrutinised, measured heat demand can be above the 15 kWh/m^{2}a goal.

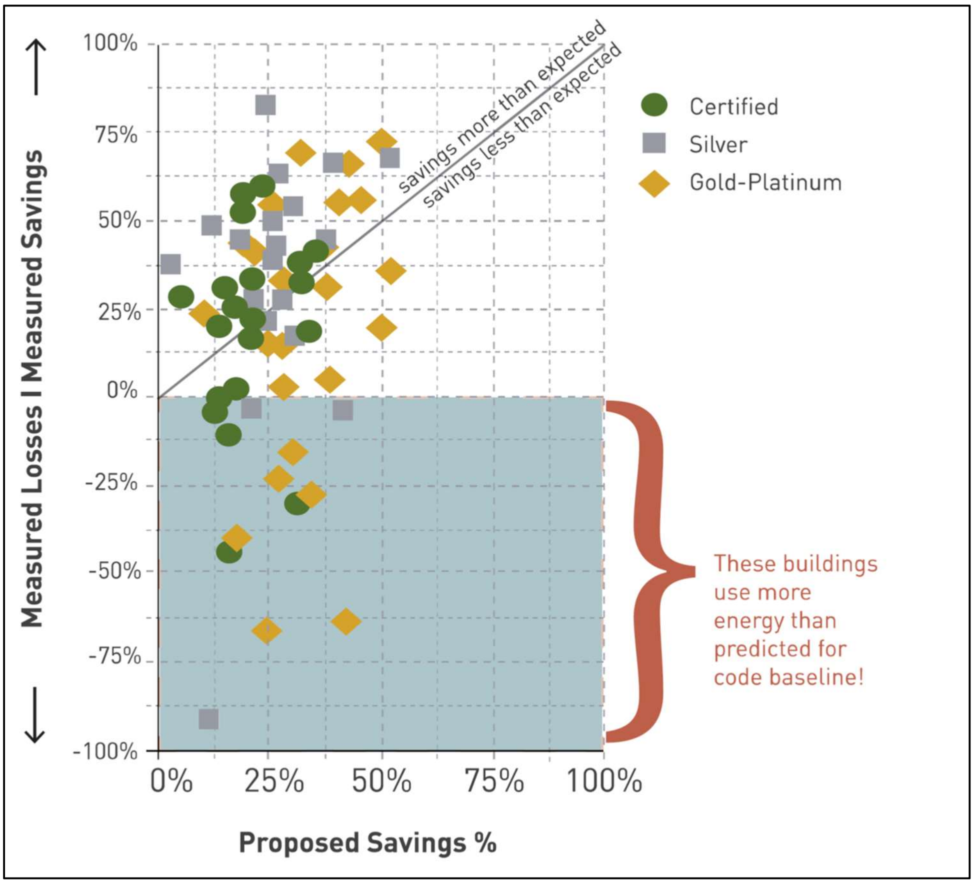


Figure 58: Results of a comparison of measured versus modelled energy performance in buildings certified under the US Green Building Council's Leadership in Energy & Environmental Design (LEED). Many buildings perform below their modelled target, with some even performing below the LEED compliance baseline. Source: (Cascasdia Green Building Council, 2011).

In 2014, the Zero Carbon Hub (ZCH) published a report looking into the causes of, and possible solutions to, the performance gap phenomenon. Amongst other things the ZCH identified the role of market forces in driving real improvements in performance noting that "*if a market advantage already existed for delivering high quality, low energy cost homes it would already be being exploited*" (Zero Carbon Hub, 2014). The perception of a lack of market demand for energy efficient dwellings, as well as a lack of relevant occupant knowledge, was also picked up as a significant barrier to zero carbon home building in a survey of construction industry participants (Heffernan, et al., 2015). However, it is notable that the survey did not include those who eventually inhabit the products of the construction industry. More recently it has been shown that, in the UK, volume house builders have been able to profit from building and selling houses of such poor quality that it is questionable whether they are compliant with UK building regulations (iNews, 2019), never mind meeting any energy efficient or zero carbon targets.

If clients of the house building industry can be persuaded to buy sub-standard houses, this does suggests a lack of knowledge of the product they are buying, or a lack of buying power, or both. It may be that fixing these problems could create the market demand needed to drive the building of the high quality, low energy cost homes that are needed. For example, the Australian NABERS framework, a performance (as opposed to design) standard applied to commercial buildings, was deliberately supported by Federal and State government requirements that they would only rent buildings rated 4.5* or better (Department of the Environment and Energy, 2019). The Property Council of Australia later made the 4.5* minimum rating a requirement for 'prime' or 'grade A' office categories. Although real estate owners can still offer lower quality office space to private companies, they will have access to a wider tenant market, and will be able to charge a premium, if they invest in upgrading their property portfolios.

It is almost inevitable that any legally mandated measures of compliance become targets that the construction industry seeks to achieve for minimal cost. As mentioned above, in relation to volume house builders, it may even be a case of developers working out what they can get away with. Given the construction industry's power to lobby governments, there is also the potential danger for ZeroCC standards to be designed/defined to achieve a 'zero' goal, but one that is based on what is easier to achieve (and therefore likely to be cheaper, and more economically attractive) than what will actually contribute to reduced carbon emissions from buildings. Real reductions in carbon emissions will require the very close alignment of any enforced measures/targets with outcomes that lead to real reduced carbon emissions from building systems when connected to the wider global system.

This thesis does not seek to provide a definition of a zero carbon building to be adopted globally. Instead it has investigated how the feature characteristics of a variety of building system objects impact the likelihood of a building achieving a zero carbon or zero energy goal globally. The approach taken has been similar in manner to how banks use the profiles and features of potential customers to determine the risk associated with the repayment of a loan.

This thesis views buildings as objects which represent building systems. The objects have associated features with defined characteristics, representing components of the building system. For example, each building object has a defined external wall surface area, the size of which depends on the shape/size of the building footprint and the height of the building. As a building component, the external walls are also assigned thermal insulation properties. The size and thermal properties attributes of the external walls, in combination with similar attributes of other components (i.e. the size and thermal properties of the windows) determines the overall thermal performance of the building envelope (e.g. how easily heat energy can travel through the building envelope). Embodied carbon and energy characteristics are also attributed to the building object components.

The Standard Building Model building system objects described in this thesis have 14 features with a variety of possible characteristics, or attributes. Some feature characteristics may have a negative impact on the achievement of the ZeroCC goal (e.g. high infiltration levels) while others may have a positive impact (e.g. a large PV array generating renewable electricity). The combination of the feature characteristics determines whether the building system object in question achieves the zero carbon, or energy, goal; if the positive impacts equal, or outweigh, the negative impacts, the building achieves the ZeroCC goal as defined in this work.

This work has identified that, contrary to usual assumptions, the features required to achieve a zero carbon building are not necessarily the same as those needed for zero energy, and are likely to change with time. Continuing the banking analogy, this represents a situation where a bank, in altering its applicant profiling algorithm, discovers a different set of potential low-risk customers within the same population of applicants that it had not realised existed; an untapped source of valuable income.

The significant influence of the occupant in the landscape of ZCBs and ZEBs is also clear in this work. While the influence of building occupants on the design of buildings may be of a secondary nature, their role in operational performance is evident. For example, a study looking at domestic energy demand in Finland concluded that per capita measures of energy demand (as opposed to the often used per unit floor area metric) give a more accurate reflection of the energy demand of buildings (Heinonen & Junnila, 2014). In addition, the domestic electricity profile shown in Figure 40, Chapter 7, demonstrates that electricity demand is strongly tied to occupant demand (largely in relation to plug loads, but also in terms of lighting). See Appendix A63 for a variety of estimated average dwelling occupancy densities around the world.

It may therefore be appropriate to treat occupants as 'energy demand carriers' that flow in and out of different building systems, with their demand profiles playing a central role in determining the kind of renewable energy generation strategy that is appropriate to apply to a zero carbon building system. Taking this approach to assessing carbon emissions from buildings, it would be reasonable to also include such things as transport requirements arising as a result of a new development – as some have previously suggested (Stephan et al. 2013a, 2012). Within this kind of ZeroCC framework short buildings with a high ratio of rooftop PV area to internal floor area might start to look less attractive given their greater need for land area, and the likelihood that they would need to be located further from facilities such as accessible public transport, local shops, workplaces and schools.

In this thesis, the building system objects are treated as individual units, whereby energy demand is site-based – although energy generation can be remotely achieved. However, in reality, and particularly in relation to carbon emissions, buildings are not standalone objects, but are part of wider local, national and global systems. Most carbon emissions are not generated at the site system level; buildings are almost always connected to an energy grid from which carbon emissions arise. Likewise, renewable energy generation does not remove carbon dioxide from the atmosphere on site. Buildings, their occupants and the energy grids that they are connected to form part of a much larger interconnected system. Even the mini-grids described in Section 4.5, where buildings are self-sufficient in terms of site energy demand/generation, are part of a global manufacturing system in which energy demand (and usually carbon emissions) result from the manufacture of the technology needed to create the mini-grids.

Given this interconnection between buildings and the wider global system, it is important to recognise that there is no such thing as a standalone zero carbon/energy building. What really makes a building beneficial from the perspective of climate change is how it performs, with regard to carbon emissions, within the global system. For example, input-output tables (described in Section 5.3 in relation to calculating the embodied carbon and energy of products) are often used in economic analysis, and recognise that costs/energy flow in and out of economic systems, but not necessarily in direct/clear routes. If buildings are treated as standalone units, in terms of a ZeroCC definition, there is a danger that important parts of the building system as a whole (i.e. the global implications of the inflow and outflow of energy/carbon emissions to and from the building system) will be missed, and negative impacts possibly exacerbated, because focus is placed on the components that are easy to measure, or are closer to the site. For example, the recently announced net zero carbon target for the UK economy to achieve by 2050 has been criticised for allowing the 'offshoring' of UK carbon emissions, as imported products and services will not be included in the UK's net carbon emissions total (CarbonBrief, 2019). This 'offshoring' of carbon emissions may be particularly pertinent in the case of ZeroCC buildings where renewable energy generating technology included in the design to achieve a zero goal is manufactured using carbon intensive energy, but the embodied carbon of the building system falls outside the scope of any ZeroCC assessment (for example, see the discussion on embodied carbon in PV in Section 5.7).

As part of the drive to reduce carbon emissions in the UK economy, the UK Government has recently invested £36 million in an Active Building Centre to encourage the UK construction industry to embrace the idea of Active Buildings. These are buildings designed to be energy efficient, integrating renewable energy technologies for heat, power and transport, with the potential to be energy self-sufficient (Active Building Centre, 2019). Although the concept does not rely on any particular renewable energy technology, its emphasis is on harvesting and storing solar energy (Engineering and Physical Sciences Research Council, 2018).

The Active Building concept, to balance energy demand against renewable energy generation, is similar in nature to many of the ZeroCC buildings and concepts described in this thesis where zero energy (as opposed to zero carbon) is the focus of attention. The SBM Zero Energy Building (ZEB) objects are defined by their ability to generate at least as much energy as they demand. The difference is that rather than the area for collecting solar energy (for example, the PV array) being limited to the size of the roof, as is the case for SBM ZEBs, this is optimised in the case of Active Buildings (i.e. potentially including building integrated PV to cover various facades of the building, not just the roof). In addition, the zero energy school described in Chapter 3 fulfils many of the Active Building requirements, although it was designed and constructed before the label was born. The school does not have the ability to store energy on site, but it balances energy demand and generation on an annual basis. Similarly prescient is the NetZEB concept described in Section 3.6, also developed before Active Buildings emerged. Site storage of energy is not necessary here either, but energy generation and demand are required to balance, and this is scrutinised on the basis of a monthly balance. Finally, the buildings served by the mini-grids described in Section 4.5 also comply with the requirements of Active Buildings. These buildings are energy self-sufficient through necessity, rather than as a result of environmental concerns, and demand is likely to be tailored to generation/storage ability rather than the other way around. Given such mini-grid systems have arisen in response to the lack of reliable and affordable energy infrastructure in developing communities, it is unlikely that they will be required to charge electric vehicles in the near future.

The Active Building initiative plans to transform the UK construction and energy sectors to drive forward efficient energy use and decarbonisation (Active Building Centre, 2019). The concept is UK-based, so an Active Building will need to be able to cope with the environmental variation that the UK seasons bring; they will need high performing thermal envelopes in order to minimise heat energy demand during the UK winter. As demonstrated by the case of the zero energy school (in Chapter 3), such thermal envelopes are likely to require Passivhaus standards of design and construction. It is a laudable aim for all new buildings to be built to this level of quality, and, if successful, it would be a significant step towards a more energy efficient building stock. However, the UK Government has previously questioned whether it is economically viable for the UK construction industry to deliver such high quality buildings (see the argument at the end of Section 4.2). The likelihood that the Active Building concept will drive improvements in this regard therefore seems to be more closely tied to the economics of the construction industry rather than what is technologically possible.

If Active Buildings are to be self-sufficient, as well as minimising energy demand, they also need to generate and store enough energy to meet their demand. Given the UK's seasonal variation in temperature (which has the effect of increasing energy demand in winter) and available solar energy (which decreases in winter), the generation and storage of energy will be a much greater challenge than that faced by the buildings with mini-grids in South Asia and Africa. For example, Appendix A48 shows the insolation data that was used in SBM for a number of different locations across the globe. The data for Oslo, at 60°N, shows that monthly average available solar radiation (on a horizontal surface) varies between 0.4 and 5.5 kWh/m^2 per day throughout the year. Not only are winters very cold in Oslo, but the sunlight that would be needed to generate the energy an Active Building may require would be in short supply. Closer to the equator it is generally warmer, there is more solar energy available for collection, and insolation levels vary less across the year. Variation in solar radiation across the year for Accra (at 6°N) is only between 4.4 and 5.4 kWh/m^2 per day.

In the case of the zero energy school, located in Exeter, UK (51°N), the seasonal variation challenge was dealt with by maximising the solar collection area such that excess PV generation in the summer would balance out the generation deficit in the winter (see Figure 21). However, the school design did not attempt to achieve real self-sufficiency. Excess generation is not stored on site, and the question of how to store excess summer generation for use in the winter was only addressed by reliance on the national electricity grid.

The need to maximise the inclusion of energy generation and storage technology in Active Buildings brings into question the issue of embodied carbon and whether the overall benefits of such an approach outweigh the costs from the perspective of climate change. It is clear that there are carbon emissions associated with energy generation, with the facilities needed for energy generation (renewable or otherwise), and with the facilities needed to store generated energy. For example, Figure 29 shows that while the production of PV generated electricity does not produce carbon emissions, the production of the technology needed to generate the electricity does result in carbon emissions. It is also clear that the carbon emissions associated with PV generated electricity vary with available insolation. For example, Table 6 estimates that almost twice the carbon emissions are associated with generating the same amount of PV electricity in Glasgow (56°N) as compared with Accra - this is simply because there is less solar energy available for collection in Glasgow, so a larger solar collection area is needed (i.e. a larger PV array) to generate the same amount of electricity. As discussed in Section 5.7, it is also true that the amount of carbon emissions associated with producing PV varies with the method and location of manufacture. Finally, any embodied carbon data found during this research has only ever considered various boundary conditions associated with the products themselves, and the issue of waste has not been discussed.

The issue of waste in the construction industry has not been included in the scope of this work as it is a substantial subject and worthy of its own thesis. However, it is clear that waste is an important issue when looking at the costs and benefits of ZeroCC buildings and frameworks, particularly in relation to embodied carbon. Alongside the materials and components that are incorporated into the finished building there are those that are not incorporated, and end up as waste. For example, an old, but interesting, study carried out by the Building Research Establishment (Skoyles, 1974) determined that the waste produced on building sites was enough to produce an extra 13,000 dwellings (based on the housing output of 1974). More recently, it has been found that up to 15% of all materials delivered to construction sites end up in skips (WRAP, 2007). Given the financial cost of PV modules, it is reasonable to expect that they would receive careful treatment when they arrive on site. However, PV modules are also fairly delicate pieces of equipment and can easily be damaged during their journey from the factory to their final position in the building. As Active Buildings plan to drive an increase in demand for renewable energy technology, it is worth considering what additional waste streams this could generate, and whether the embodied carbon tied up in them is outweighed by the benefits the technology brings. In a global assessment of the total cumulative net benefit of PV, Louwen et al. (2016) concluded that break-even between the disadvantages and benefits of PV occurred sometime between 1997 and 2018. This suggests that in general increased global deployment of PV in future can only be a good thing, and therefore the Active Building drive to increase such technology will be beneficial. However, the article notes that insolation and consequently location are of great importance in the assessment of benefits, so concentrating PV deployment in a localised manner maybe more problematic. It is also notable that the article does not mention waste and the embodied carbon costs associated with PV that is produced but never successfully put to good use.

In terms of defining what a zero carbon building is, the question is really how to ensure the long term, sustainable construction of buildings that do not contribute to climate change. The far-reaching transitions that the IPCC have identified are needed will require buildings to go beyond simply passing a standalone energy ‘test’. Real ZeroCC buildings need to be designed and constructed with an understanding of how these systems plug into, and impact, CO_2 emissions in the global system as a whole.

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Appendix

A1. Typical annual UK household demand for energy and resulting carbon emissions[2]

Electricity Demand	kWh/a	$kgCO_2$
Fridges and Freezers	545	283
Washing Machine	170	88
Tumble Dryer	342	177
Dishwasher	313	162
Cookers and Ovens	460	239
Small kitchen appliances	150	78
Lighting	477	248
Computers and Printers	241	125
TV, DVD, CD, Radio etc.	565	293
	3,263	**1,693**
Heating demand	**kWh/a**	**$kgCO_2$**
Domestic Hot Water	3,160	683
Space Heating	4,680	1,011
	7,840	**1,693**
Totals	**11,103**	**3,387**

Assuming[3]

	$kgCO_2/kWh$
UK Gas	0.216
UK Electricity	0.519

[2] Based on Energy Savings Trust, 2012. *Powering the Nation: Household electricity-using habits revealed,* London: Energy Savings Trust.

[3] From Department of Energy and Climate Change, 2012. *The Government's Standard Assessment Procedure for Energy Rating of Dwellings.* Watford: BRE.

A2. Embodied energy measurements in windows

Windows contribute significantly to the energy performance of a building, particularly in relation to lighting and heating[4], for example note the significance of heat loss through windows compared with the rest of the building envelope Figure 27. Windows are also significant in relation to the environmental cost of construction and maintenance[5][6][7]. The variety of potential assessment boundaries is perhaps not surprising given the variety of window functions and properties, and these may have a positive or negative effect on energy demand.

Figure 59 shows a simple representation of a window lifecycle, and demonstrates that the calculation of associated energy costs and savings is influenced by the point at which the assessment boundary is drawn; in terms of both the life cycle stage (represented horizontally here), and what is included at each relevant stage (represented vertically here). Although the assessment of embodied energy (EE) is usually focused on the energy required to produce a product, in the case of the lifecycle of windows some authors extend the boundary to include operational aspects such as solar gain (for example, Abeysundra, et al., (2007) in Table 57).

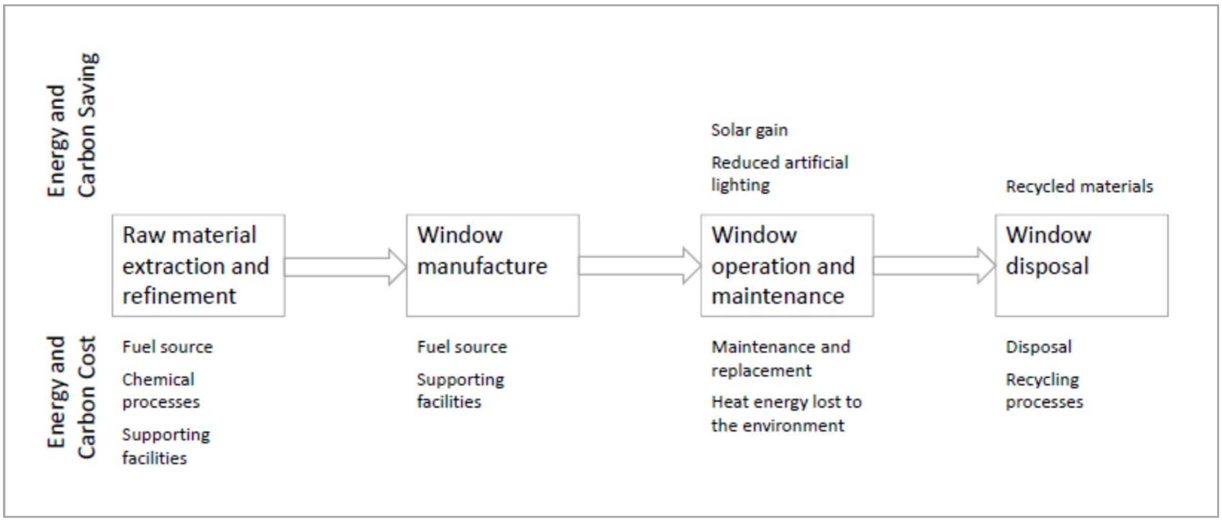

Figure 59: Simplified window lifecycle.

At a minimum windows perform a dual role in the building envelope; as a barrier separating the internal and external environments, mainly in relation to heat transfer; and as a bridge, allowing daylight and solar energy to enter. On the one hand the provision of daylight and solar gains (in cold climates) can help reduce the energy demand of a building, but on the other hand windows tend to allow heat to transfer out more readily than the rest of the building envelope leading to increased energy demand. In addition to the manufacturing and maintenance costs, these 'operational' costs and benefits have been included to different degrees in the assessment of the environmental cost of windows in different studies. Table 57 presents window EEs along with brief explanations of the boundaries

[4] Brown, A. W., Allwinkle, S. J. & Weir, G. F., 1999. Evaluating the sustainability of alternative window and proprietary glazing systems. *Durability of Building Materials and Components,* 8(1-4), pp. 1973-1982.
[5] Menzies, G. F. & Wherrett, J. R., 2005. Windows in the workplace: examining issues of environmental sustainability and occupant comfort in the selection of multi-glazed windows. *Energy and Buildings,* Issue 37, pp. 623-630.
[6] Tian, C., Chen, T., Yang, H. & Chung, T. M., 2010. A generalized window energy rating system for typical office buildings. *Solar Energy,* Issue 84, pp. 1232-1243.
[7] Radhi, H. & Sharples, S., 2013. Global warming implications for facade parameters: A life cycle assessment of residential buildings in Bahrain. *Environmental Impact Assessment Review,* Issue 38, pp. 99-108.

used in the respective calculations. All values are based on the process method for EE analysis.

Table 57 demonstrates that:

- The calculated EE of a window is dramatically affected by the boundary conditions used in the calculation.
- The material used in the window frame has a significant impact on the EE calculated[89].
- As manufactured components, it is difficult to treat windows as homogeneous elements of the building (e.g. like insulation) and calculate embodied energy values per m^2 of glazing.
- Including glazing in the façade of a building can have a positive impact on the energy use of a building (e.g. energy required for lighting is reduced)[10]. This suggests the use of windows could be viewed as an energy efficiency measure where the energy cost can be balanced against the energy savings arising from their inclusion.

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[8] Asif, M., Davidson, A. & Muneer, T., 2002. *Life Cycle of Window Materials: A comparative assessment.* [Online] Available at: http://www.cibse.org/pdfs/Masif.pdf [Accessed 28 October 2013].

[9] see and Saito and Shukaya (1996) in Dutil, Y. & Rousse, D., 2012. Energy costs of energy savings in buildings: A review. *Sustainability,* Issue 4, pp. 1711-1732.

[10] Tian, C., Chen, T., Yang, H. & Chung, T. M., 2010. A generalized window energy rating system for typical office buildings. *Solar Energy,* Issue 84, pp. 1232-1243.

Table 57: Embodied energies of windows with varying calculation boundaries.

Source	Window type	Unit Size	EE (MJ)/unit	Notes
(Radhi & Sharples, 2013)[11]	Glass (material)	$1m^2$	333.4	Calculation Boundary: material extraction and manufacturing Original value in kWh – conversion using 1kWh = 3.6MJ
	Aluminium (frame)	n/a	775.8	
	Aluminium double glazing (Value based on 1.2m x 1.2m unit)	$1m^2$	1246.3	
(Monahan & Powell, 2011)[12]			31.78 MJ/kg of window	Based on 1277kg of windows and 40,584MJ of primary energy
(Tian, et al., 2010)[13]	Clear8	Not specified	15.9	Calculation Boundary: Annualised embodied energy consumption/m^2 (window EE + operating energy required for cooling and lighting) Location: Hong Kong
	ClearV8	Not specified	6.5	
	Clear15.6	Not specified	20.7	
	ClearV15.6	Not specified	11.3	
	Bronze8	Not specified	15.9	
	Bronze15.6	Not specified	18.6	
	BG (Blue-green)	Not specified	14.7	
	AE (Advantage evergreen)	Not specified	14.7	
	EAL (Energy advantage low-E	Not specified	14.5	
	RL (Reflective low-E on clear)	Not specified	14.6	
	RLV (Reflective low-E on clear)	Not specified	5.1	
	BL (Blue low-E on clear)	Not specified	14.6	
	GC (Generic clear)	Not specified	18.4	
(Hammond & Jones, 2009)[14]	uPVC window	1.2m x 1.2m	2300	Calculation boundary: "as appropriate for 'cradle-to-site' studies"
(Abeysundra, et al., 2007)[15]	Timber window (Assumes 60% of timber is used as firewood at the end of the window's life. Otherwise EE = 1184.83MJ)	1.829m x 1.219m	-2307.07	Calculation Boundary: Embodied energy consumption (cradle-to-grave EE + operational energy savings)
	Aluminium window (Includes iron grills for security)	1.829m x 1.219m	7479.6	
(Syrrakou, et al., 2004)[16]	Electrochromic glazing unit (no frame)	0.4m x 0.4m	49	Calculation Boundary: Manufacture of component materials only (not manufacture of unit)
	K-Glass	0.4m x 0.4m	32.1 (10.7MJ/kg of K-glass)	
Recio et al. (2005) cited in: (Salazar & Sowlati, 2008)[17]	Wood framed window	Not specified	74.5	Not specified
	Virgin PVC double glazed	Not specified	253.6	
	PVC 30% recycled double glazed	Not specified	214	
	Virgin aluminium double glazed	Not specified	1981.1	
	Aluminium 30% recycled double glazed	Not specified	1406.5	
(Asif, et al., 2002)[18]	Aluminium frame	1.2m x 1.2m	6000	Calculation Boundary: Cradle-to-grave
	PVC	1.2m x 1.2m	2980	
	Al-clad timber	1.2m x 1.2m	1460	
	Timber	1.2m x 1.2m	995	
(Weir & Muneer, 1998)[19]	Double-glazed – Argon filled	1.2m x 1.2m	1030.51	Calculation Boundary: EE of materials and manufacturing processes
	Double-glazed – Krypton filled	1.2m x 1.2m	1538.7	
	Double-glazed – Xenon filled	1.2m x 1.2m	5530.5	
Saito and Shukuya (1996) cited in: (Dutil & Rousse, 2012)[20]	Aluminium single glazed	$1.02m^2$	2190	Not specified
	Aluminium double glazed	$1.02m^2$	2319	
	Timber double glazed	$1.02m^2$	463	

[11] Radhi, H. & Sharples, S., 2013. Global warming implications for facade parameters: A life cycle assessment of residential buildings in Bahrain. *Environmental Impact Assessment Review,* Issue 38, pp. 99-108.
[12] Monahan, J. & Powell, J. C., 2011. A comparison of the energy and carbon implications of new systems of energy provision in new build housing in the UK. *Energy Policy,* Issue 39, pp. 290-298.

[13] Tian, C., Chen, T., Yang, H. & Chung, T. M., 2010. A generalized window energy rating system for typical office buildings. *Solar Energy,* Issue 84, pp. 1232-1243.
[14] Hammond, G., Jones, C., Lowrie, F. & Ise, P., 2011. *Embodied Carbon: the Inventory of Carbon and Energy (ICE).* Bracknell: BSRIA.
[15] Abeysundra, U. G. Y., Babel, S., Gheewala, S. & Sharp, A., 2007. Environmental, economic and social analysis of materials for doors and windows in Sri Lanka. *Building and Environment,* Issue 42, pp. 2141-2149.
[16] Syrrakou, E., Papaefthimiou, S. & Yianoulis, P., 2004. Environmental assessment of electrochromic glazing production. *Solar Energy Materials and Solar Cells,* Issue 85, pp. 205-240.
[17] Salazar, J. & Sowlati, T., 2008. A review of life-cycle assessment of windows. *Forest Products Journal,* Issue 58, pp. 91-96.
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[19] Weir, G. & Muneer, T., 1998. Energy and environmental impact analysis of double-glazed windows. *Energy Conversion and Management,* Issue 39, pp. 243-256.
[20] Dutil, Y. & Rousse, D., 2012. Energy costs of energy savings in buildings: A review. *Sustainability,* Issue 4, pp. 1711-1732.

A3. Estimated PV embodied carbon based on PVCIs quoted in literature[21]

PV embodied carbon calculation (estimating embodied carbon from PVCI)

$$PV\ embodied\ carbon(kgCO_2e) = PVCI(kgCO_2e/kWh) \times Lifetime\ generation(kWh)$$

PV electricity generation calculation

$$Lifetime\ generation(kWh) = PVyield(\%) \times Insolation(kWh) \times PerformanceRatio \times Lifetime(years)$$

For CdTe PV in USA **Embodied energy = 1,200 MJ/$m^2_{primary}$** **Estimated embodied carbon = 59 $kgCO_2e/m^2_{PV}$** **(Assuming primary energy factor and electricity grid CI below)**	**USA**
Yield (%)	9
Insolation (kWh/m^2a)	1,800
Performance ratio	0.8
Lifetime (years)	30
Lifetime PV generation (kWh/m^2_{PV})	**3,900**
Electricity grid CI ($kgCO_2e/kWh$)[22]	0.613
Primary energy conversion efficiency for USA[21]	0.29
PVCI ($kgCO_2e/kWh$)	0.018 (stated)
PV embodied carbon ($kgCO_2e/m^2_{PV}$) (0.018 x 3,900)	**70** **(estimated)**
PV embodied carbon ($kgCO_2e/m^2_{PV}$) (1,200 x 0.29 / 3.6) x 0.613	**59** **(estimated)**

PV embodied carbon calculation (estimating PVCI from embodied energy)

$$PVCI(kgCO_2e/kWh) = \frac{PV\ embodied\ carbon(kgCO_2e)}{Lifetime\ generation(kWh)}$$

For CdTe PV in Germany **Embodied energy = 1,100 MJ/$m^2_{primary}$** **Estimated embodied carbon = 33 $kgCO_2e/m^2_{PV}$** **(Assuming primary energy factor and electricity grid CI below)**	Germany
Yield (%)	8
Insolation (kWh/m^2a)	1,700
Performance ratio	0.75
Lifetime (years)	30
Lifetime PV generation (kWh/m^2)	**3,000**
Electricity grid CI ($kgCO_2e/kWh$)[22]	0.353
Primary energy conversion efficiency for Germany[21]	0.31
PVCI ($kgCO_2e/kWh$) (33 / 3000)	**0.011** **(estimated)**
PV embodied carbon ($kgCO_2e/m^2_{PV}$) (1,100 x 0.31 / 3.6) x 0.353	**33** **(estimated)**

[21] Embodied energy, and primary energy conversion, values from:
Fthenakis, V. M. & Kim, H. C., 2011. Photovoltaics: Life-cycle analyses. *Solar Energy,* pp. 1609-1628.

[22] MacKay, D. J. C., 2009. *Sustainable Energy - without the hot air.* Cambridge: UIT Cambridge Ltd.

A5. SBM relationship between logit(ZEB) and insolation levels

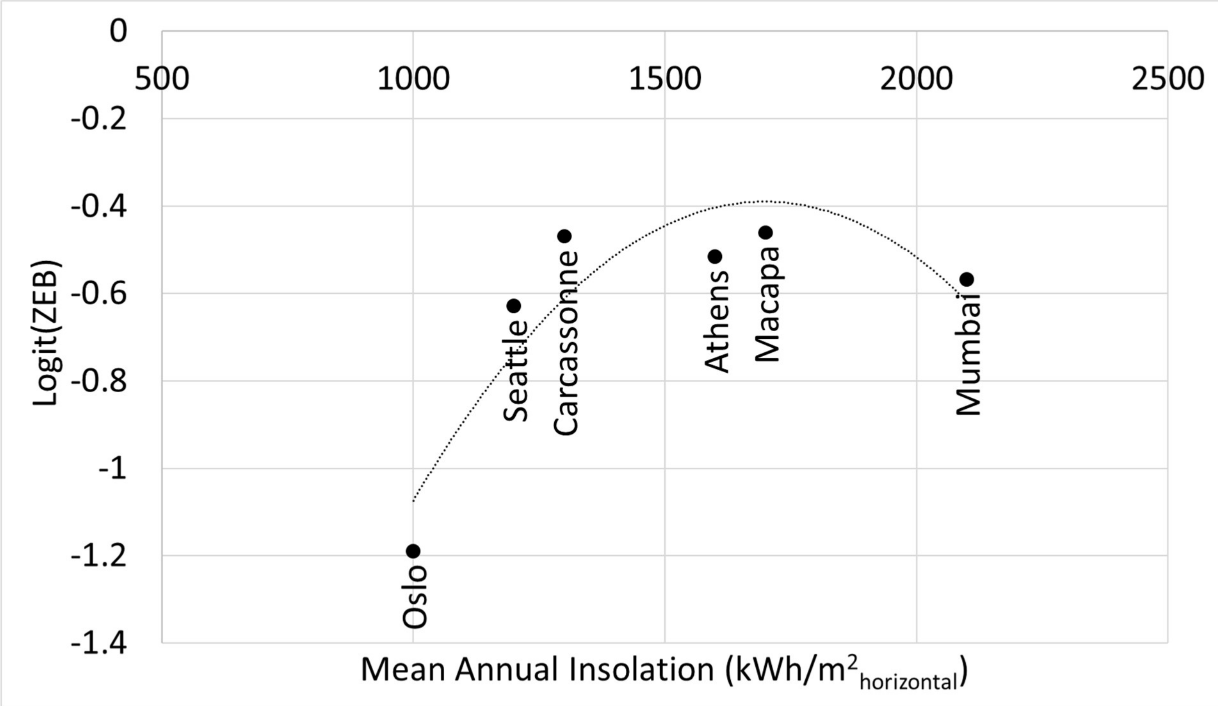

Figure 60: Graph showing the SBM relationship between Logit(ZEB) and mean annual insolation.

A6. The Total Energy Model (TEM)

The Total Energy Model (TEM) was developed to quantify the embodied energy cost of a building, including initial construction, recurring maintenance and associated waste. TEM is similar to the Passivhaus Planning Package (PHPP) developed by the Passivhaus Institute (Cotterell & Dadeby, 2012) in that it consists of an Excel workbook containing a number of worksheets. The purpose of TEM is to enable the calculation of, and transparent comparison between, the embodied energy costs of any type of building with any design life. The Bill of Quantities (BoQ) for the construction project assessed provides the input values for material quantities and costs. The TEM calculation is based on the hybrid method for embodied energy calculation described in (Acquaye et al., 2011).

The TEM workbook covers initial embodied energy (from materials, components and activities used in construction) and recurring embodied energy (from the maintenance of the building). All items in the bill of quantities are included, as even activities that do not result in a tangible product still require some form of direct or indirect energy input. The TEM initial embodied energy is calculated according to Equation 10. The mass of building material, expenditure on standalone components and expenditure on miscellaneous items in the BoQ are inputs obtained from the building project's BoQ. The variables are described in Table 58.

Equation 10: Initial embodied energy (EE) calculation in MJ

$$Initial\ EE = \sum_{x=1}^{n} M_x e_x + \sum_{y=1}^{m} S_y\, i_y + B \sum_{z=1}^{l} R_z$$

Table 58: Descriptions of TEM variables.

Variable	Unit	Description	Notes
M_x	kg	Mass of building material	Masses of material items in the BoQ.
e_x	MJ/kg	Process energy intensity of building material *x*	Random variables determined from the minimum, average and maximum figures provided by the ICE database[23]. Labelled 'Materials' in TEM
S_y	£	Expenditure on standalone components	Cost of component items in the BoQ (for example, windows).
i_y	MJ/£	Total (I-O) energy intensity of product producing sector (non-construction)	Values obtained from the Office for National Statistics Energy Intensity by Industry tables[24]. Labelled 'Components' in TEM
B	MJ/£	Total (I-O) energy intensity of construction sector	Values obtained from the Office for National Statistics Energy Intensity by Industry tables. Labelled 'Other' in TEM
R_z	£	Expenditure on miscellaneous items	Cost of items in the BoQ that are not materials or components (for example, groundworks).

[23] Hammond, G., Jones, C., Lowrie, F. & Ise, P., 2011. *Embodied Carbon: the Inventory of Carbon and Energy (ICE).* Bracknell: BSRIA.
[24] Office for National Statistics, 2013. *Energy Intensity by Industry, 1997-2011* (Excel Sheet) [Online]. Available from: http://www.ons.gov.uk/ons/rel/environmental/uk-environmental-accounts/2013/rft-energy-intensity-by-industry.xls [Accessed 9 April 2014]

The *Initial EE* calculation can be repeated as necessary for items/materials that are replaced/maintained during the life of the building according to Equation 2.

Equation 2. Calculation of recurrence of initial EE

$$Recurrence\ no. = \frac{Building\ Life}{Item\ Life}$$

The following are examples of the TEM worksheets. The data in the worksheets comes from a recently completed school building designed to be zero-energy in use (Montgomery School, Exeter).

E8 =SUM(Components!E:E)

B	C	D	E	F	G	H
Building Life (Yrs)	99		Project Value (£)	7,536,130.00		
Initial EE (MJ)				Recurring EE (MJ)		Totals
Materials	Expected	0		0		0
	Var	0		0		
	S.d.	0		0		
Components			12,901,281		46,146,780	59,048,061
Other			3,812,888		3,956,559	7,769,447
						66,817,508
Initial Waste EE (MJ)				Recurring Waste EE (MJ)		Totals
Materials	Expected	0		0		0
	Var.	0		0		
	S.d.	0		0		
Components			14,446		29,824	44,270
Other			13,373,366		16,942,374	30,315,740
						30,360,010
Totals			30,101,982		67,075,536	97,177,518

Building Info | BoQ Items | Materials | Components | Other | Waste | Sector EEs

Figure 61: The *Building Info* worksheet showing the TEM output.

A2 Item

BoQ Item Item	Total cost	Life (yrs)	Type	No. Replacements required	Waste product type
Substructure	£436,587	99	Other	0	Concrete (17 01 01)
Frame	£926,657	99	Other	0	Metals (17 04 07)
Allowance for upper floors based upon Buchan costs Included in Buchan quote 27/11/9	£214,044	99	Other	0	Mixed (17 09 04)
Fire protection to steel beams	£5,682	40	Other	1.475	Binders (17 01 01)
Glazed roof light area	£63,298	40	Component	1.475	Mixed (17 09 04)
Roof Plant Steelwork	£5,682	25	Component	2.96	Metals (17 04 07)
Column to support - galvanised steel columns to act as downpipes as per breakdown in final account for canopy works (CE200)	£20,676	30	Component	2.3	Metals (17 04 07)
Carpentry as per breakdown in final account for canopy works (CE200)	£9,932	30	Other	2.3	Timber (17 02 01)
Roof covering as per breakdown in final account for canopy works (CE200)	£10,136	30	Component	2.3	Tiles and Ceramics (17 01 03)
Aluminium cappings as per breakdown in final account for canopy works (CE200)	£21,124	30	Component	2.3	Metals (17 04 07)
Edge protection to raised areas on roof	£21,224	25	Other	2.96	Mixed (17 09 04)
Roof timberwork - lining to parapets & form upstands	£23,630	20	Other	3.95	Timber (17 02 01)
Parapet Panels to roof area	£38,326	20	Other	3.95	Mixed (17 09 04)
Roof Covering - ballast	£20,600	60	Other	0.65	Soils (17 05 04)
Weatherproof PV Cables	£5,682	60	Component	0.65	Plastics (17 02 03)
Aluminium Copings - Zone 3	£11,595	40	Component	1.475	Metals (17 04 07)
Aluminium Copings - Zone 2	£11,595	40	Component	1.475	Metals (17 04 07)
Aluminium Copings - Zone 1	£11,595	40	Component	1.475	Metals (17 04 07)

Building Info | BoQ Items | Materials | Components | Other | Waste | Sector EEs | Item Typ ...

Figure 62: The *BoQ Items* worksheet showing the input Bill of Quantities information.

E3 =IF(A3=FALSE,"FALSE",(B3*D3))

	BoQ Material	Mass (kg)	ICE Material	Average ICE EE (MJ/kg)	Material EE (MJ)	ICE EE s.d.	ICE EE Var.	Recurring EE (MJ)	Recurring Var.	Waste Estimate (kg)	Waste EE (MJ)	Recur. Waste EE (MJ)
3	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
4	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
5	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
6	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
7	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
8	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
9	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
10	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
11	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
12	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
13	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
14	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
15	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
16	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
17	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
18	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
19	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
20	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
21	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
22	FALSE	FALSE		#N/A	FALSE	#N/A	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

Building Info | BoQ Items | Materials | Components | Other | Waste | Sector EEs | Item Type ...

Figure 63: The *Materials* worksheet showing the items in the *BoQ Items* worksheet defined as ‘materials’.

A73 =IF('BoQ Items'!H73="Component",'BoQ Items'!A73)

	BoQ Component	Total Component Cost (£)	Sector	Sector Energy Intensity (TJ/£m)	Component EE (MJ)	Recurring EE (MJ)	Waste Estimate (£)	Waste EE (MJ)	Recur. Waste EE (MJ)
3	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
4	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
5	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
6	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
7	Glazed roof l	63297.61	Manufacture of glass, refractory, clay, other porcelain and ceramic products,	40.51265963	2564354.53	3782422.9	238,889.68	9678.056	14275.1332
8	Roof Plant St	5682.36	Fabricated metal products, except machinery and equipment, excluding we	5.807173537	32998.4506	97675.414	1,595.18	9.263464	27.41985278
9	Column to su	20676	Manufacture of basic Iron & Steel	66.04791336	1365606.66	3140895.3	5,804.25	383.3588	881.7253353
10	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
11	Roof coverin	10136.46	Other manufactured goods	7.901105239	80089.2372	184205.25	626.13	4.947138	11.37841648
12	Aluminium c	21124.48	Fabricated metal products, except machinery and equipment, excluding we	5.807173537	122673.521	282149.1	5,930.15	34.43743	79.20608113
13	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
14	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
15	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
16	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE
17	Weatherpro	5682.361724	Rubber & plastics products	27.66983739	157230.025	102199.52	1,218.97	33.72881	21.92372684
18	Aluminium (	11594.98411	Fabricated metal products, except machinery and equipment, excluding we	5.807173537	67334.0849	99317.775	3,254.99	18.90231	27.88090337
19	Aluminium (	11594.98411	Fabricated metal products, except machinery and equipment, excluding we	5.807173537	67334.0849	99317.775	3,254.99	18.90231	27.88090337
20	Aluminium (	11594.98411	Fabricated metal products, except machinery and equipment, excluding we	5.807173537	67334.0849	99317.775	3,254.99	18.90231	27.88090337
21	FALSE	FALSE		#N/A	FALSE	FALSE	FALSE	FALSE	FALSE

Building Info | BoQ Items | Materials | Components | Other | Waste | Sector EEs | Item Type ...

Figure 64: The *Components* worksheet showing the items in the *BoQ items* worksheet defined as ‘components’.

A1

	BoQ Other Items	Total Other Item Cost (£)	Other Item EE (MJ)	Recurring EE (MJ)	Waste Estimate (£)	Waste EE (MJ)	Recur. Waste EE (MJ)		Construction Industry Energy Intensity (MJ/£)	1.24620516
3	Substructure	436587.28	544077.3	0	559962.1	697827.6	0			
4	Frame	926657.33	1154805	0	260135.1	324181.8	0			
5	Allowance for upper floors based upon Bucha	214044.22	266743	0	807818.1	1006707	0			
6	Fire protection to steel beams	5682.36	7081.386	10445.04	59.17222	73.74072	108.7676			
7	FALSE	FALSE	0	0	FALSE	0	0			
8	FALSE	FALSE	0	0	FALSE	0	0			
9	FALSE	FALSE	0	0	FALSE	0	0			
10	Carpentry as per breakdown in final account f	9932	12377.31	28467.81	10242.69	12764.49	29358.33			
11	FALSE	FALSE	0	0	FALSE	0	0			
12	FALSE	FALSE	0	0	FALSE	0	0			
13	Edge protection to raised areas on roof	21224.04	26449.51	78290.54	80101.04	99822.33	295474.1			
14	Roof timberwork - lining to parapets & form u	23630.16	29448.03	116319.7	24369.35	30369.2	119958.4			
15	Parapet Panels to roof area	38326.45	47762.62	188662.3	144646.7	180259.5	712025.1			
16	Roof Covering - ballast	20599.69772	25671.45	16686.44	298882.5	372468.9	242104.8			
17	FALSE	FALSE	0	0	FALSE	0	0			
18	FALSE	FALSE	0	0	FALSE	0	0			
19	FALSE	FALSE	0	0	FALSE	0	0			
20	FALSE	FALSE	0	0	FALSE	0	0			
21	Roof Covering - walkways	20989.50774	26157.23	17002.2	1296.529	1615.741	1050.231			

Building Info | BoQ Items | Materials | Components | Other | Waste | Sector EEs | Item Type ...

Figure 65: The *Other* worksheet showing the items in the *BoQ items* worksheet not defined as either ‘materials’ or ‘components’.

Energy intensity by industry

UK Resident basis — Terajoules(TJ)/£million

	Industrial sector	2004	2005	2006	2007	2008	2009	2010	2011
A	Products of agriculture, hunting and related services	16.04598335	14.99185222	15.09039261	15.1835685	14.4716288	15.41059765	16.52031014	16.90650077
A	Products of forestry, logging and related services	12.2622807	8.312901121	7.599608063	7.740225803	7.616873953	6.422693509	6.169146745	5.811896584
A	Fish and other fishing products; aquaculture products; support services to fi	15.9009275	15.53470177	15.83469173	15.25455848	20.69327709	14.72945097	14.8800529	12.36850786
B	Mining of coal and lignite	9.87171416	11.08381278	11.44281121	12.69885137	13.71399052	14.04360049	14.03165376	12.43032626
B	Crude petroleum and natural gas	8.505742921	9.097068268	9.488374641	9.260759766	9.546798429	10.35079306	11.1163427	12.21281135
	Mining and quarrying of metal ores and other products and support service:	4.777197665	5.507837521	3.780605468	3.733989264	4.811408808	4.886789943	4.564878301	4.326763227
C	Manufacture of vegetable and animal oils and fats	10.74053049	8.11575137	6.550432107	6.033135059	5.733241001	4.999310557	5.331749802	7.793090633
C	Manufacture of grain mill products, starches and starch products	18.18901244	12.60008074	18.91625354	18.26896908	17.78385941	16.35668652	16.96913856	17.80677812
C	Textiles	23.71427925	25.67990892	24.74433951	24.28277274	23.6449421	19.44731945	18.23821496	19.81050034
C	Leather and related products	6.144815395	6.371984802	9.061497596	8.531391311	8.591166326	8.569181782	8.402617451	6.817110184
C	Wood and of products of wood and cork, except furniture; articles of straw	17.23950589	18.53618536	20.15113536	18.74864496	19.81793931	21.99537999	24.610385	25.77083872
C	Paper and paper products	44.45688158	49.58290013	52.28208081	49.32451693	49.68631751	47.7293529	47.0113897	51.09163033
C	Printing and recording services	10.25006769	10.56630096	8.612929643	8.682584045	8.675612797	7.779472328	8.003193803	8.349577815
	Manufacture of coke oven & refined petroleum products	180.9751342	184.0654078	191.0944296	180.8057202	200.6986438	212.4311003	213.0095633	219.8701238
C	Manufacture of industrial gases and non-nitrogen-based inorganic chemica	32.00532929	38.85523669	37.73370719	40.51122302	38.94398916	40.53382817	38.84974126	38.96783784
C	Manufacture of petrochemicals	46.15672805	38.33063964	38.03585856	37.60490621	35.28825936	46.05242493	50.10611585	43.04642513
C	Manufacture of paints, varnishes & ink	5.152785086	4.71686079	4.875495104	5.641134023	5.507406794	5.969912901	5.253833361	4.845463268
C	Manufacture of cleaning & toilet preparations	8.095074228	9.613547629	9.746256444	9.482457745	8.182300159	6.292023205	6.482452682	5.587066651
C	Manufacture of other chemical products & man-made fibres	11.2927046	14.23932063	11.76859081	13.25161522	12.87247888	11.38551628	13.64197052	15.06153037

Building Info | BoQ Items | Materials | Components | Other | Waste | Sector EEs | Item Type ...

Figure 66: The *Sector EEs* worksheet showing the energy intensities of different industries applied to the different components.

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE
Aggregate	**37**	**0.11**	**0.12**	**0.01**	**0.50**
Predominantly Recycled	3	0.25	0.21	0.10	0.40
Unspecified	17	0.11	0.07	0.02	0.28
Virgin	17	0.10	0.15	0.01	0.50
Aluminium	**111**	**157.1**	**104.7**	**8.0**	**382.7**
50% Recycled	4	108.6	53.4	58.0	184.0
Other Specification	3	146.5	79.3	55.0	193.5
Predominantly Recycled	28	17.9	8.7	8.0	42.9
Unspecified	14	169.1	67.0	68.0	249.9
Virgin	62	224.1	68.5	39.2	382.7
Asphalt	**17**	**6.63**	**11.89**	**0.20**	**50.20**
Predominantly Recycled	2	7.32	0.28	7.12	7.52
Unspecified	13	7.46	13.47	0.23	50.20
Virgin	2	0.49	0.40	0.20	0.77
Bitumen	**7**	**17.91**	**20.21**	**2.40**	**50.00**
Unspecified	6	20.50	20.84	3.38	50.00
Virgin	1	2.40	2.40	2.40	-
Brass	**9**	**80.70**	**71.87**	**16.81**	**239.00**
Other Specification	1	39.00	39.00	39.00	-
Predominantly Recycled	1	20.00	20.00	20.00	-
Unspecified	5	113.95	72.67	62.00	239.00

... | BoQ Items | Materials | Components | Other | Waste | Sector EEs | Item Types | ICE EEs

Figure 67: The *ICE EEs* worksheet showing the energy intensities of different materials.

A8. The Virtual Building Model (VBM)

The Virtual Building Model (VBM) was developed to quantify the lifetime energy demand and carbon emissions associated with a building, including embodied energy and carbon, energy demand and carbon emissions associated with heat demand and renewable energy generated by a roof-mounted photovoltaic array. VBM is an Excel workbook, similar to PHPP and TEM, but the embodied energy/carbon calculation is based on the process method (rather than the hybrid method used in TEM). In addition, rather than using the BoQ as the direct input to the model, VBM uses design specifications (i.e. the external wall construction and size) to determine the embodied energy and carbon values and the thermal properties of the thermal envelope.

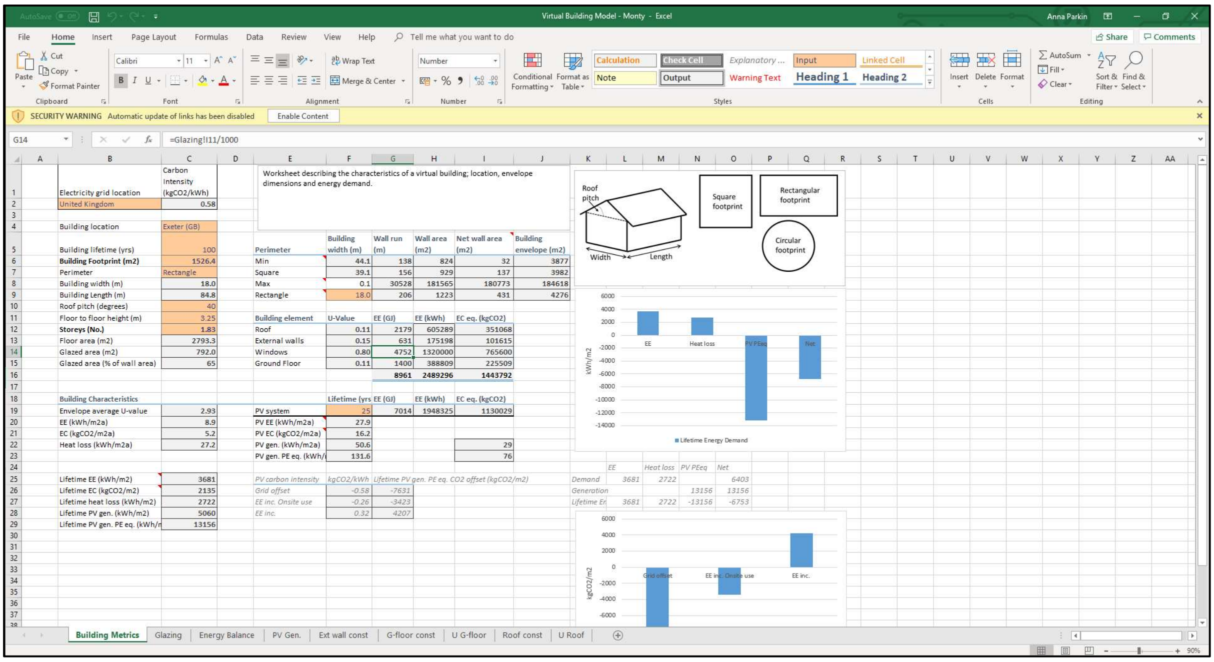

Figure 68: The *Building Metrics* worksheet describing the characteristics of a virtual building; location, envelope dimensions and heat energy demand. The input values (peach cells) are based on Montgomery School, Exeter.

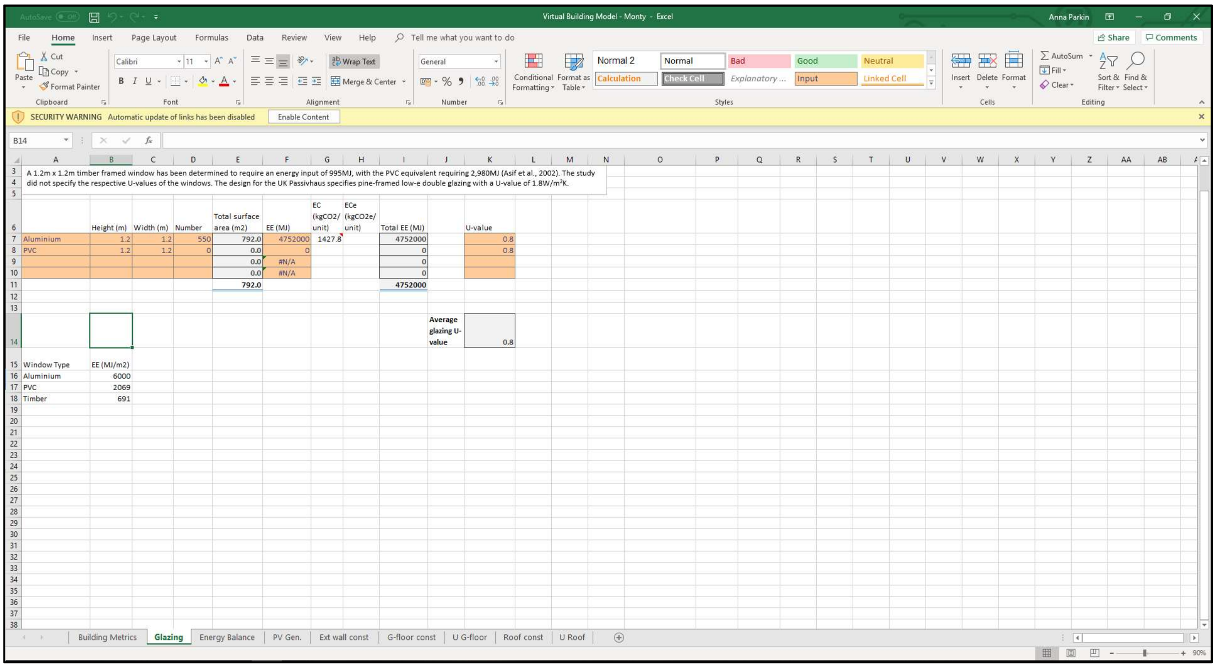

Figure 69: The *Glazing* worksheet describing the properties of the glazing.

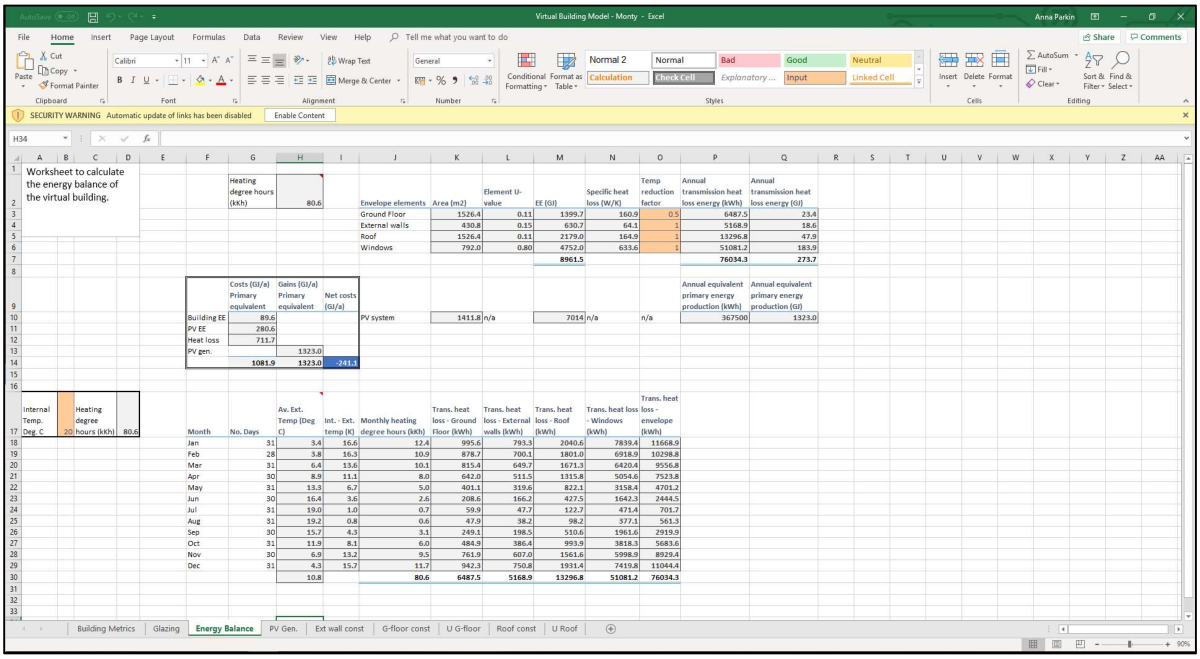

Figure 70: The *Energy Balance* worksheet calculating the energy balance of the virtual building.

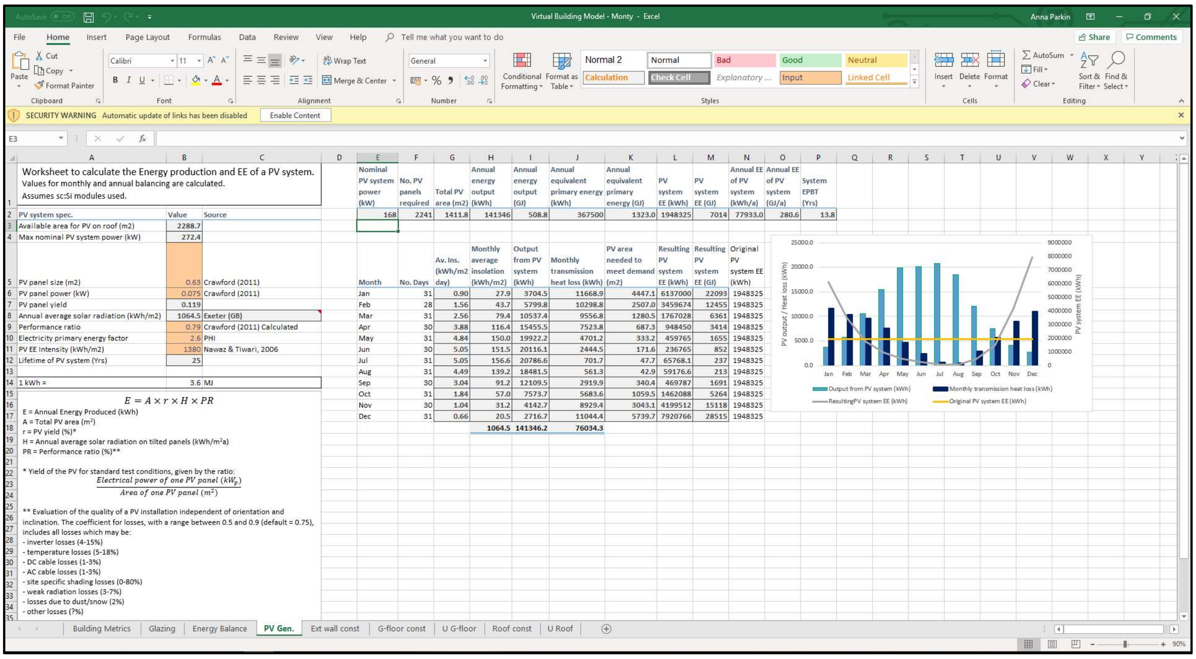

Figure 71: The *PV Gen.* worksheet calculating the energy generation and embodied energy of the PV array.

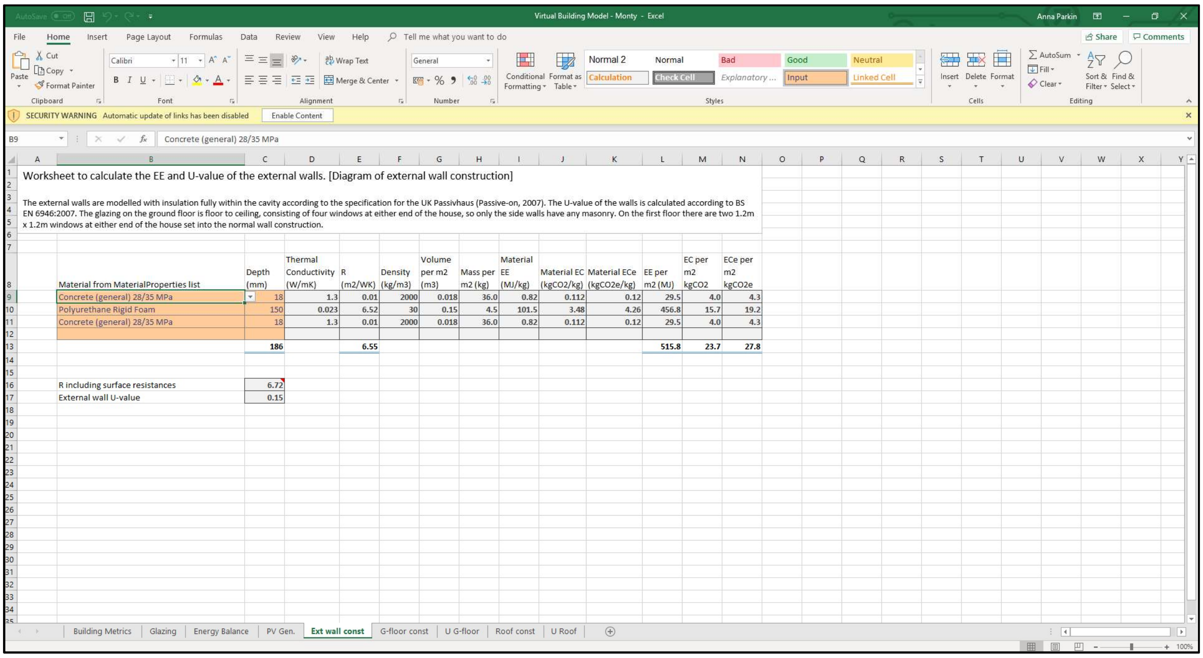

Figure 72: The *Ext wall const* worksheet calculating the embodied energy and the thermal properties of the external walls.

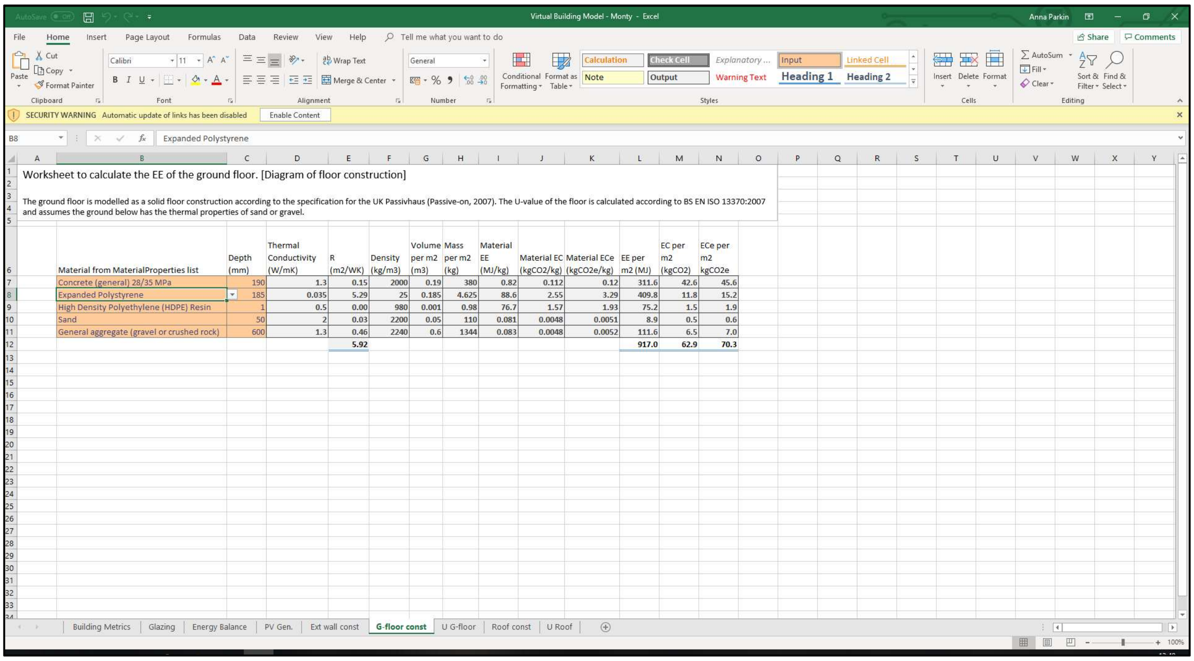

Figure 73: The *G-floor const* worksheet calculating the embodied energy of the ground floor.

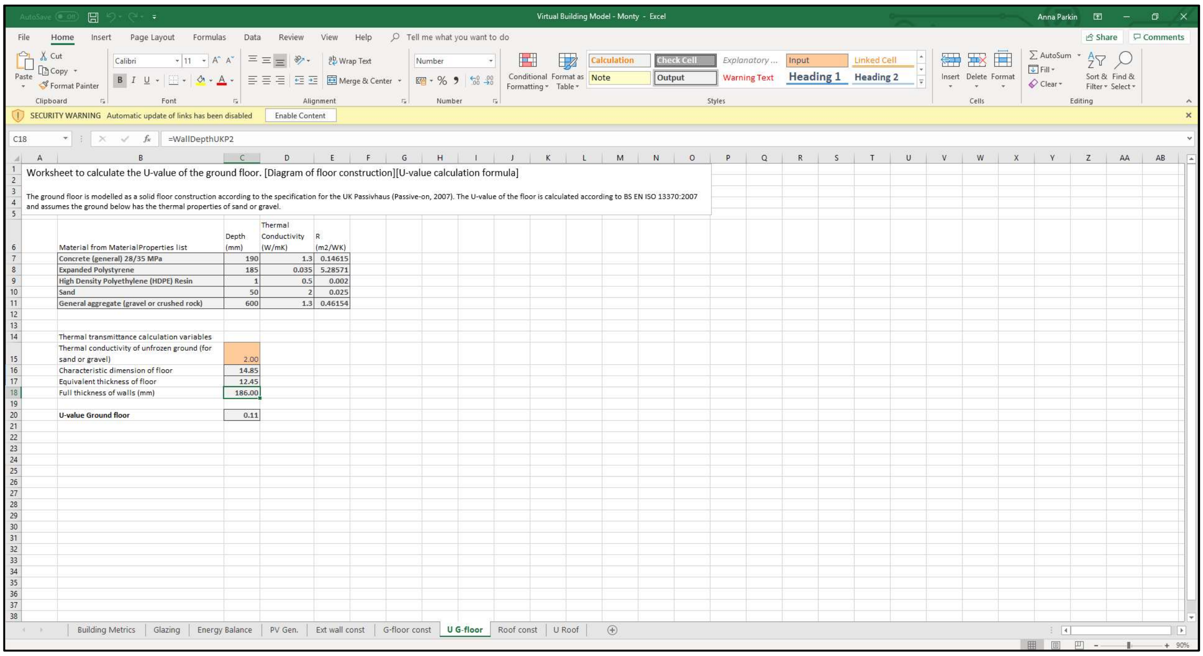

Figure 74: The *U G-floor* worksheet calculating the thermal properties of the ground floor.

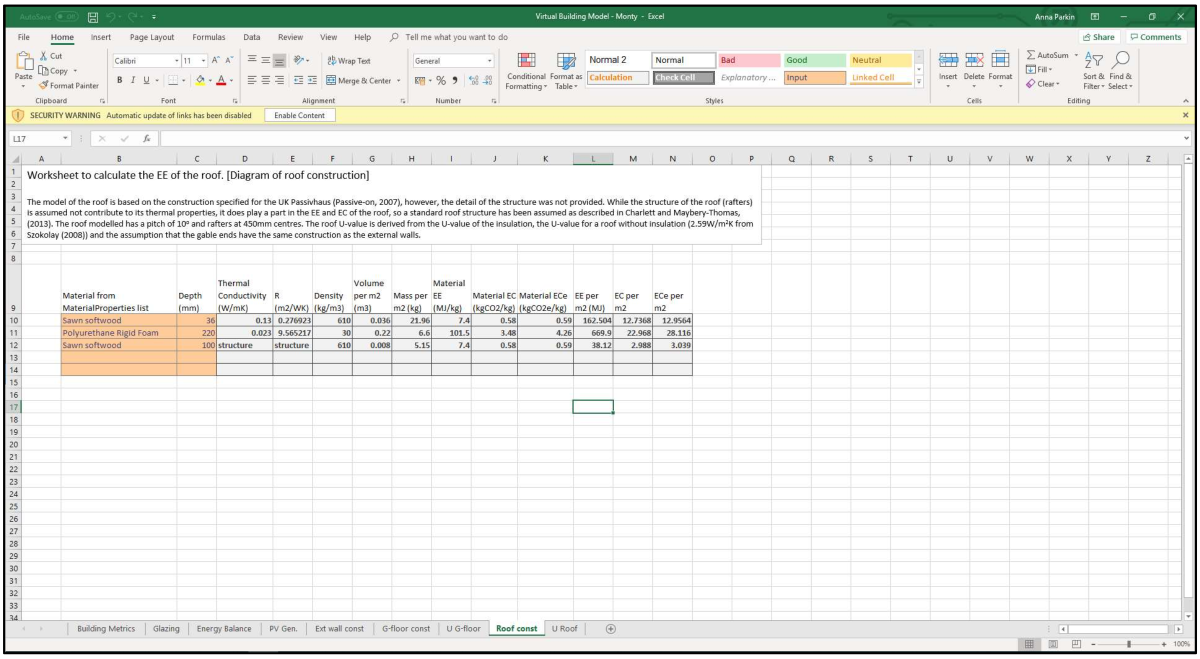

Figure 75: The *Roof const* worksheet calculating the embodied energy of the roof.

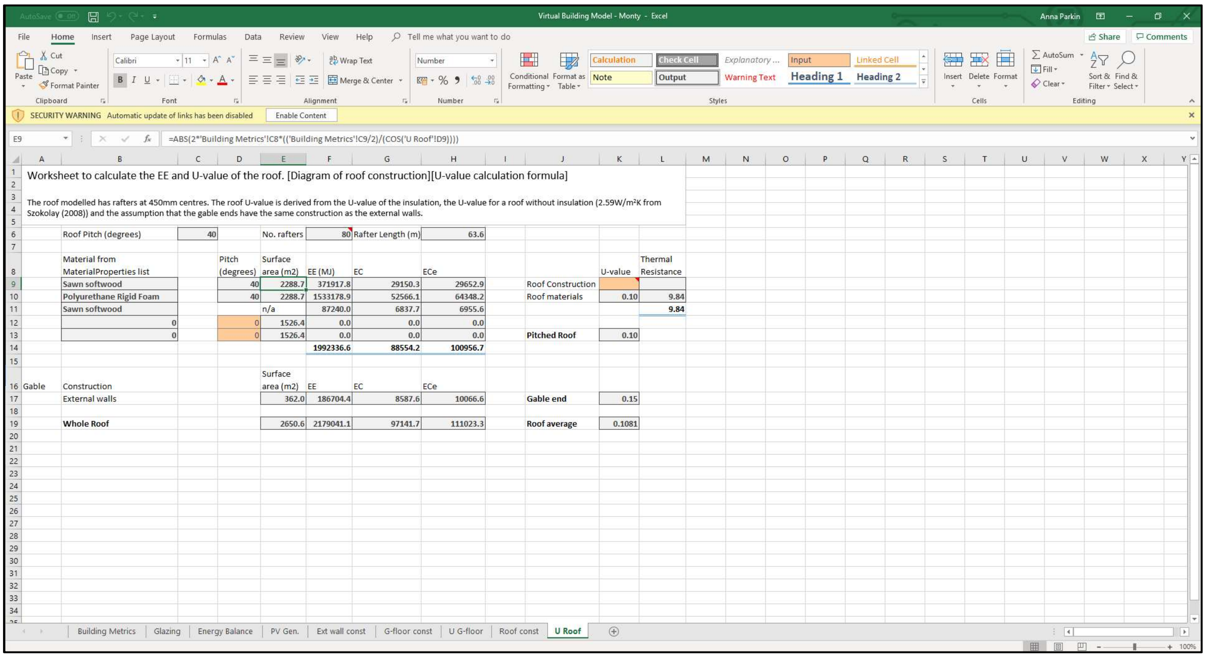

Figure 76: The *U Roof* worksheet calculating the thermal properties of the roof.

A10. Building Lifetime and Operational Carbon tool (BLOC)

BLOC is an online tool that calculates the annualised lifetime carbon emissions from a building as specified by the user, including embodied carbon, operational carbon emissions from heating and electricity demand and carbon emissions offset from PV generation. BLOC can be found at the following link http://people.bath.ac.uk/abp28/helloworld

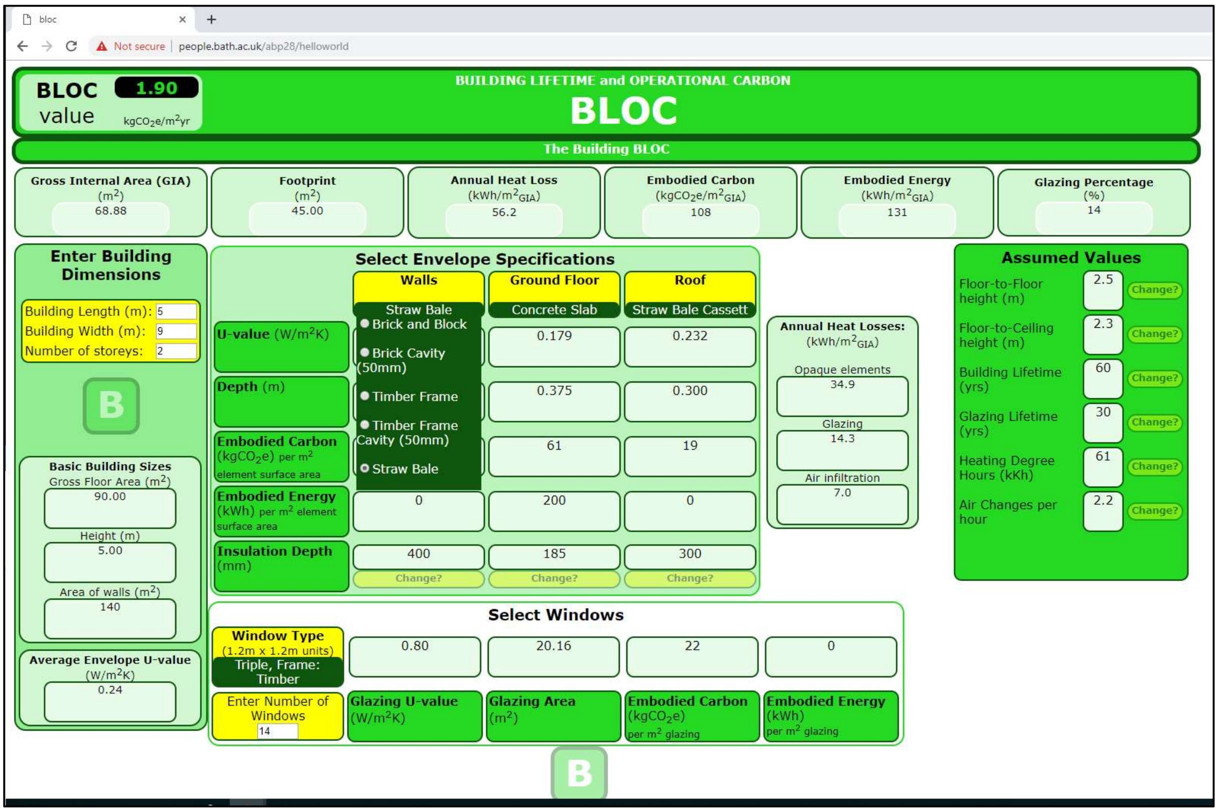

Figure 77: Image of the online tool BLOC.

A12. The Standard Building Model (SBM)

13/09/17 21:28 C:\Users\Anna\Desktop\MATLAB\SBM...\SBM.m 1 of 1

```
% Assign imported data to matrices/vectors
assignMatrices
% Start Simple Building Model
SBMconstants
% Define imported data (external walls, ground floor, roof, windows)
SBMbuildSpec
wallU1
floorU1
roofU1
winArea1
editWinArea

thermEnv1

EnvEE

exTemp
annInsoUni1;
PV1;

domThermal1
SBMdomDem;
domHG1;
domHeating1
domCooling1

%WeeklyCO = ((elecCI/ifa) .* sum(houseDDannual)) - ((PVelecCI/ifa) .* sum(PVoutWeek)) + WeeklyEC + ((gasCI/1000) .* sum(absHin));
%Weekly carbon balance = electricity demand CO2 - PV generation CO2 +
%Weekly EC cost of building + active heating CO2 (kgCO2/m2)
%WeeklyCOcost = (WeeklyCO > 0) .* WeeklyCO;
%Only taking the positive carbon costs
%AnnWeeklyCO = ((sum(WeeklyCOcost)/12)*52);
%Positive carbon costs summed over the year

SBMZCB

%SBMannualEC;

```

A14. assignMatrices.m

13/09/17 21:29 C:\Users\Anna\Desktop...\assignMatrices.m 1 of 1

```
%TestS2 is the external wall data (Lw)
Lw = TestS2;

%TestS3 is the ground floor data (Lf)
Lf = TestS3;

%TestS4 is the roof data (Lr)
Lr = TestS4;

%TestS5 is the glazing data (W)
W = TestS5;
```

A15. SBMconstants.m


```
%Primary energy factor
PEfact = 0.315;  %European primary energy factor = 0.315 (Advanced payback time...↙
, 2011)

%Surface Resistances (m^2K/W)
Rse = 0.04;                 %External surface resistance
RsiU = 0.10;                %Internal surface resistance Upward
RsiH = 0.13;                %Internal surface resistance Horizontal
RsiD = 0.17;                %Internal surface resistance Downward

%Thermal conductivity of ground (W/mK)
k_ground = 2;               %Thermal conductivity of unfrozen ground for sand or↙
gravel (or where soil type unknown)

%Wind screen factor (0.04 - 0.1) to de-rate from 50Pa - typically 0.07
wsf = 0.07;

Tocc = 18; % input('Enter occupied heating set point (Deg. C):');     %Heating set↙
point when building occupied
Tuno = 13; % input('Enter unoccupied heating set point (Deg. C):');   %Heating set↙
point when building unoccupied

%External temperature above which cooling is desirable (deg. C) (occupied
%cooling set point)
CoolTemp = 25;
CoolTempUno = 30;   %(unoccupied cooling set point)

%occDens = 35;      %Occupant density (m2/person)

human = 125;       %Metabolic heat gains (W/person)
utilisation = 0.55;       %Interior heat availability factor in PHPP

%Emissions kgCO2 per kWh energy - SAP 2012
gasCI = 0.216;              %Carbon intensity of UK mains gas (for heating) 0.216
%elecCI = 0.610;               %Carbon Intensity of UK electricity (or at building↙
location)    see importInsolation.m
%PVelecCI = 0.610;          %Carbon Intensity of electricity grid at PV location↙
see importInsolation.m
if elecCI < gasCI
    gasCI = elecCI;
end
%PV EC (Inventory of Carbon and Energy has 242 kgCO2/m2 for monocrystalline
%PV modules - estimated from EE of 4750 MJ/m2 and assuming typical
%industrial fuel mix.
%PVec = 149;
%PVee = 241; %kWh (not primary)
% PVec and PVee based on (Advanced payback time..., 2011): monocrystalline
% silicon (2,750 MJprimary per m2 PV), European PE factor 0.315
%batteryEC = 283; %kgCO2e for a NiMH battery to store 220 kWh daily (energy for one↙
person's needs)
%batteryEE = 458; %kWh assuming European electricity CI = 0.617 kgCO2e/kWh
batteryLife = 15; %years
%PV spec
performanceRatio = 0.79;            %See Virtual Building Model UK.xlsx
%disp(['PV performance ratio (%): ' num2str(performanceRatio)])
```

```
%cellSize = input('Enter the size of one PV cell (m2): ');
%cellPower = input('Enter the power of one PV cell (kW): ');
cellSize = 0.63;
cellPower = 0.075;

%MVHR efficiency (PH minimum efficiency requirement is ...%)
MVHReff = 0.9;
%MVHR EC: Based on cost of MVHR system in Montgomery School, energy
%intensities of UK economic sectors in 2012, and CO2 emissions from electricity use
%in the UK in 2011 (DUKES)
MVHREC = 3.3; %kgCO2e/m2(ifa)a
MVHREE = 7.3; %kWh/m2a non-prim
%MVHR lifetime

%Heating system EC: Based on Embodied Carbon and Building Services (CIBSE
%Research Report 9)
%Heating appliance: 5 kgCO2eq/product
%Installed: add 19 kgCO2eq/m3
Boiler = 5;
BoilerVol = 19;
BoilerLif = 15; % ??? %

%Building lifetime (a)
buildLife = 60;

%Glazing lifetime
glazLife = 30;
GLF = floor(buildLife / glazLife);  %Glazing Lifetime Factor - no times glazing to be replaced in building lifetime.
if GLF < 1
    GLF = 1;
end

%PV lifetime (a)
PVLife = 30;

%Internal building elements
%IntFec = 34;     %kgCO2e per m2 floor area - CONCRETE
%IntFee = 64;     %kWhprim per m2 floor area - CONCRETE
%IntFec = -92;    %kgCO2e per m2 floor area - Profideck Seq (Hayesfield School)
%IntFec = 26;     %kgCO2e per m2 floor area - Profideck exSeq
%IntFee = 207;    %kWhprim per m2 floor area - Profideck exSeq

%IntWec = -94;    %kgCO2e per m2 surface area - CLT Seq (Hayesfield School)
%IntWec = 27;     %kgCO2e per m2 surface area - CLT exSeq (Hayesfield School)
%IntWee = 211;    %kWhprim per m2 surface area - CLT (Hayesfield School)
```

A16. SBMbuildSpec.m


```
%Description of the building metrics

%a_ground = 45; % input('Enter building footprint (m^2):');        %Building footprint
%width = 5; % input('Enter building width (m):');                  %Building width
%storeys = 20; % input('Enter number of storeys:');                %No. storeys
f2f = 3; % input('Enter floor-to-floor height (m):');            %Floor-to-floor height
f2c = 2.5; % input('Enter floor-to-ceiling height (m):');          %Floor-to-ceiling height

% disp(['Building footprint = ', num2str(a_ground), ' m^2'])
% disp(['Building width = ', num2str(width), ' m'])

length = a_ground/width;                                       %Building length
% disp(['Building length = ', num2str(length), ' m'])

p_ground = 2*(width + length);                                 %Footprint perimeter
% disp(['Building perimeter length = ', num2str(p_ground), ' m'])

height = storeys * f2f;                                        %Total wall height
% disp(['Height of walls = ', num2str(height), ' m'])

a_vertical = height * p_ground;                                %Total vertical surface area (walls and windows)
% disp(['Surface area of walls and windows = ', num2str(a_vertical), ' m2'])
```

A17. wallU1.m


```
wallDk = Lw';       %Transpose Lw to allow row vectors D (describing the depths of the layers) and k (describing the conductiviy of the layers) to be extracted as row vectors

%disp('D is a row vector describing the depth (m) of each wall layer')
%disp(['D has ', num2str(wLayers), ' elements'])
Dw = wallDk(1,:);     %Extract first row of Dk as row vector D

%disp('k is a row vector describing the conductivity (W/mK) of each wall layer')
%disp(['k has ', num2str(wLayers), ' elements'])
kw = wallDk(2,:);     %Extract second row of Dk as row vector k

%disp('EC is a row vector describing the Embodied Carbon (kgCO2) per m2 surface area of each wall layer')
%disp(['EC has ', num2str(wLayers), ' elements'])
ECw = wallDk(3,:);     %Extract third row of wallDk as row vector ECw
matECw = ECw./Dw;       %matEC gives EC per m2 surface area per m depth of each material

% The thermal resistance of a layer is given by the following:
%   Thermal resistance (m^2K/W) = layer thickness (m) / layer
%   conductivity (W/mK)

%R = D / k

%disp('Rw is a row vector describing the thermal resistance (m^2K/W) of each wall layer')
Rw = Dw./kw;

%The total thermal resistance of an element is given by the following:
%   Total thermal resistance (m^2K/W) = Internal surface resistance (RsiH) + Thermal
%   resitance layer 1 + Thermal resistance layer 2 + ... + Thermal resistance
%   layer n + External surface resistance (Rse)
wRes = RsiH + Rse + sum(Rw);     %see Constants.m for RsiH and Rse values

wU = 1/wRes;    %U-value = 1 / Total thermal resistance of element
wDep = sum(Dw);  %Total wall depth = sum of elements in Dw
wEC = sum((Dw.*matECw)); %EC (kgCO2) of all wall layers per m2 surface area of wall
%disp(['Wall thermal resistance (m^2K/W): ', num2str(wRes)])
%disp(['Wall U-value (W/m^2K): ', num2str(wU)])
% disp(['Wall depth (m): ', num2str(wDep)])
%disp(['Wall EC per m2 (kgCO2): ', num2str(wEC)])
```

A18. floorU1.m


```
floorDk = Lf';        %Transpose Lf to allow row vectors D (describing the depths of the layers) and k (describing the conductiviy of the layers) to be extracted as row vectors
                      %and EC (describing the EC per m2 of the layers)
%disp('Df is a row vector describing the depth (m) of each floor layer')
%disp(['Df has ', num2str(fLayers), ' elements'])
Df = floorDk(1,:);      %Extract first row of floorDk as row vector Df

%disp('kf is a row vector describing the conductivity (W/mK) of each floor layer')
%disp(['kf has ', num2str(fLayers), ' elements'])
kf = floorDk(2,:);      %Extract second row of floorDk as row vector kf

%disp('EC is a row vector describing the Embodied Carbon (kgCO2) per m2 surface area of each floor layer')
%disp(['EC has ', num2str(wLayers), ' elements'])
ECf = floorDk(3,:);       %Extract third row of floorDk as row vector ECf
matECf = ECf./Df;         %matEC gives EC per m2 surface area per m depth of each material


% The thermal resistance of a layer is given by the following:
%   Thermal resistance (m^2K/W) = layer thickness (m) / layer
%   conductivity (W/mK)

%R = D / k

%disp('Rf is a row vector describing the thermal resistance (m^2K/W) of each floor layer')
Rf = Df./kf;

%The equivalent thickness of the floor is given by the following:
% Equivalent thickness (eqThick) = Total wall depth (wDep) + Thermal conductivity of the
% ground (k_ground) * (Internal surface resistance (RsiD) + Thermal
%   resitance layer 1 + Thermal resistance layer 2 + ... + Thermal resistance
%   layer n + External surface resistance (Rse))
eqThick = wDep + k_ground*(RsiD + Rse + sum(Rf));   %see constants.m for RsiH and Rse value

%The charateristic dimension of the floor is given by the following:
%Characteristic dimension (B) = ground floor area (a_ground) / (0.5 * ground
%floor perimeter (p_ground))
B = a_ground/(0.5*p_ground);

%The ground floor U-value calculation depends upon the relationship between
%the equivalent thickness (eqThick) and the characteristic dimension (B) of
%the floor.
%If eqThick < B, the grounq floor U-value is calculated as follows:
fU1 = (((2*k_ground)/((pi*B)+eqThick))*log(((pi*B)/eqThick)+1));
%If eqThick >= B, the ground floor U-value is calculated as follows:
fU2 = k_ground/((0.457*B)+eqThick);

if eqThick < B
    fU = fU1;
else
```

```
    fU = fU2;
end;

fDep = sum(Df);  %Total floor depth = sum of elements in Df
fEC = sum((Df.*matECf)); %EC (kgCO2) of all wall layers per m2 surface area of floor
%disp(['Floor thermal resistance (m^2K/W): ', num2str(fRes)])
%disp(['Floor U-value (W/m^2K): ', num2str(fU)])
% disp(['Floor depth (m): ', num2str(fDep)])
%disp(['Floor EC per m2 (kgCO2): ', num2str(fEC)])
```

A19. roofU1.m


```
roofDk = Lr';        %Transpose Lr to allow row vectors D (describing the depths of the layers) and k (describing the conductiviy of the layers) to be extracted as row vectors
%disp('D is a row vector describing the depth (m) of each roof layer')
%disp(['D has ', num2str(rLayers), ' elements'])
Dr = roofDk(1,:);      %Extract first row of roofDk as row vector Dr
%disp('k is a row vector describing the conductivity (W/mK) of each roof layer')
%disp(['k has ', num2str(rLayers), ' elements'])
kr = roofDk(2,:);      %Extract second row of roofDk as row vector kr
%disp('EC is a row vector describing the Embodied Carbon (kgCO2) per m2 surface area of each roof layer')
%disp(['EC has ', num2str(wLayers), ' elements'])
ECr = roofDk(3,:);      %Extract third row of roofDk as row vector ECr
matECr = ECr./Dr;        %matEC gives EC per m2 surface area per m depth of each material
% The thermal resistance of a layer is given by the following:
%   Thermal resistance (m^2K/W) = layer thickness (m) / layer
%   conductivity (W/mK)
%R = D / k
%disp('Rr is a row vector describing the thermal resistance (m^2K/W) of each homogeneous roof layer')
Rr = Dr./kr;
%The total thermal resistance of an element is given by the following:
%   Total thermal resistance (m^2K/W) = Internal surface resistance (RsiH) + Thermal
%   resitance layer 1 + Thermal resistance layer 2 + ... + Thermal resistance
%   layer n + External surface resistance (Rse)
rRes = RsiU + Rse + sum(Rr) + (1/2.59);      %see Constants.m for RsiH and Rse values
                                            %2.59 W/m^2K is the U-Value
                                            %given for a roof without
                                            %insulation in Szokolay (2008)
rU = 1/rRes;        %U-value = 1 / Total thermal resistance of element
rDep = sum(Dr);      %Total depth of homogeneous roof layers = sum of elements in Dr
rEC = sum((Dr.*matECr)); %EC (kgCO2) of all wall layers per m2 surface area of wall
%disp(['Roof thermal resistance (m^2K/W): ', num2str(rRes)])
%disp(['Roof U-value (W/m^2K): ', num2str(rU)])
% disp(['Depth of homogeneous roof layers (m): ', num2str(rDep)])
%disp(['Roof EC per m2 (kgCO2): ', num2str(rEC)])
rEC = rEC + 12.86; %Extra EC (kgCO2e/m2) for roof sructure and covering
```

A20. winArea1.m

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```
% Import WindowsS2
Wt = W';        %Transpose W to allow row vectors to be extracted
                     %Wh describing the heights of each windows type
                     %Ww describing the widths of each window type
                     %Wn describing the number of each window type
                     %Wu describing the U-values of each window type
                     %Wec describing the EC per unit of each window type

Wh = Wt(1,:);   %Extract the first row of Wt as row vector Wh
Ww = Wt(2,:);   %Extract the second row of Wt as row vector Ww
Wn = Wt(3,:);   %Extract the third row of Wt as row vector Wn
Wu = Wt(4,:);   %Extract the fourth row of Wt as row vector Wu
Wec = Wt(5,:);   %Extract the fifth row of Wt as row vector Wec

WtArea = Wh.*Ww.*Wn;                 %Row vector describing the total surface area of each window type
glazArea = sum(WtArea);              %Total surface area of glazing (m^2)
%glazU = sum(WtArea.*Wu)/glazArea;   %Average U-value of glazing (W/m^2K)
%glazU = 0.8;                        %Specify the average U-value of glazing(W/m^2K)
glazEC = sum(Wn.*Wec);               %Total EC of glazing (kgCO2)
glazECsaTot = glazEC / glazArea;        %Glazing EC per m2 surface area, based on initial specification
glazECsa = glazECsaTot * GLF;           %GLF in SBMconstants
% disp(['Total glazing area (m^2): ', num2str(glazArea)])
%disp(['Average glazing U-value (W/m^2K): ', num2str(glazU)])
% disp(['Total glazing EC (kgCO2): ', num2str(glazEC)])
```

A21. editWinArea.m


```
%glazPerc = 17; %input('Enter new glazing percentage: ');
oneWind = Wn/(100*(glazArea/a_vertical));  % No. windows for 1% glazing(vector)
windNo = round((oneWind * glazPerc));

newW = [W(:,1) W(:,2) windNo' W(:,4) W(:,5)];
W = newW;

winArea1

%thermEnv
%exTemp
%PVoutput


```

A22. themEnv1.m

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```
roofangle = 0; % input('Enter angle of roof from the horizontal (deg.):');

a_roof = a_ground / cos((roofangle * 2 * pi())/360);  %Roof area (m^2) = building footprint (m^2) modified by roof angle
a_wall = a_vertical - glazArea;             %Surface area of walls

% disp('E = [Element U-value (W/m2K)   Element Area (m2)   Element EC/m2 (kgCO2)]')
% disp('Element order by row: Ground floor, Walls, Glazing, Roof')

E = [fU a_ground fEC;wU a_wall wEC;glazU glazArea glazECsa;rU a_roof rEC];

Env = E';
Eu = Env(1,:);
Ea = Env(2,:);
Eec = Env(3,:);

%Temperature reduction factors for envelope elements. Element order: Ground floor, Walls, Glazing, Roof
trf = [0.5 1 1 1];

EnvU = sum(Eu .* Ea)/sum(Ea);                                  %sum(Ea) = area of building envelope
EnvHF = sum(Eu .* Ea);                                         %Envelope heat flow rate (W/K)
% disp(['Envelope average U-value = ', num2str(EnvU)])

EnvEC = sum(Ea .* Eec);                                        %Total envelope EC
% disp(['Envelope total EC (kgCO2) = ', num2str(EnvEC)])

ifaCalc = ((width - (2*wDep)) * (length - (2*wDep)))*storeys;       %Internal floor area
intArea = ((width - (2*wDep)) * (length - (2*wDep)));               %Internal floor area 1 storey
if intArea > 25                                                     %Internal floor area 1 storey must be greater than 25 m2
    ifa = ifaCalc;
else
    ifa = 0;
end
% disp(['Internal Floor Area (m^2) = ', num2str(ifa)])
% test to check for sensible width:height aspect ratios
aspectTest = width / height;
if aspectTest > 0.125
    pass = 1;
else
    pass = 0;
end
ifa = ifa * pass;

iav = ifa * f2c;                                               %Internal air volume
% disp(['Internal air volume = ' num2str(iav), ' m^3'])


%Ventilation required for good indoor air quality (Passivhaus standard)
```

```
%Ventilation = No. People * 30m3/h
%No. People = Treated floor area (m2) / 35m2
PHach = ((30/35) * ifa) / iav;
% disp(['PH recommended ach (1/h) for good indoor air quality: ' num2str(PHach)]);
%Nach = 0.042; % input('Enter infiltration rate (air changes per hour):');  %↙
Natural ventilation/infiltration rate

%MVHR = 1; % input('MVHR present for good indoor air quality? (1 = yes; 0 = no):');
ach = Nach + (MVHR * PHach * (1 - MVHReff));
%Air change difference between natural ventilation and effective air change
%rate given MVHR - see SBMconstants.m for MVHReff
MVHRdiff = MVHR * PHach * MVHReff;

% disp(['Effective air change rate (1/h): ' num2str(ach)])

HLvent = ach * iav * 0.33;                                  %Ventilation heat↙
flow rate (W/K)
% Heat capacity of air = 0.33 Wh/m3K (based on Passivhaus notes and
% Szokolay, 2008)
% disp(['Ventilation heat flow rate (W/K) = ', num2str(HLvent)])
% disp(['Envelope heat flow rate (W/K) = ', num2str(EnvHF)])

```

A23. EnvEE


```
wallEE
floorEE
roofEE
winEE

% Matrix describing the U-value, surface area, EC, EE of each building
% envelope element
Eee = [fU a_ground fEC fEE;wU a_wall wEC wEE;glazU glazArea glazECsa glazEEsa;rU a_roof rEC rEE];

EnvEe = Eee';
EEe = EnvEe(4,:);        %Extract envelope element EEs


EnvEEtot = sum(Ea .* EEe);                    %Total envelope EE (kWh)

AnnEnvEE = EnvEEtot / (ifa * buildLife);
% disp(['Building envelope EE (kWh/m2a): ' num2str(AnnEnvEE)]);
```

A24. wallEE


```
% Import Walls1 from data library. EEs in MJprimary. 1 kWh = 3.6 MJ. Primary
% energy factor in SBMconstants.m

wallDkEE = Walls1';       %Transpose Walls1 to allow row vector describing the EE of the layers to be extracted as a row vector
%Dw = wallDk(1,:);     %Extract first row of Dk as row vector D

EEwPrim = wallDkEE(4,:);      %Extract fourth row of wallDkEE as row vector EEw (MJPrim)

EEw = (EEwPrim * PEfact) / 3.6;      %EEs in kWh non-primary

matEEw = EEw./Dw;        %matEEw gives EE per m2 surface area per m depth of each material

wEE = sum((Dw.*matEEw)); %EE (kWh non-primary) of all wall layers per m2 surface area of wall

```

A25. floorEE


```
% Import GFloor1 from data library. EEs in MJprimary. 1 kWh = 3.6 MJ. Primary
% energy factor in SBMconstants.m

floorDkEE = GFloor1';       %Transpose GFloor1 to allow row vector describing the EE of the layers to be extracted as a row vector
%Df = floorDk(1,:);     %Extract first row of floorDk as row vector Df

EEfPrim = floorDkEE(4,:);      %Extract fourth row of floorDkEE as row vector EEf (MJPrim)

EEf = (EEfPrim * PEfact) / 3.6;      %EEs in kWh non-primary

matEEf = EEf./Df;        %matEEw gives EE per m2 surface area per m depth of each material

fEE = sum((Df.*matEEf)); %EE (kWh non-primary) of all wall layers per m2 surface area of wall

```

A26. roofEE

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```
% Import Roof1 from data library. EEs in MJprimary. 1 kWh = 3.6 MJ. Primary
% energy factor in SBMconstants.m

roofDkEE = Roof1';        %Transpose Roof1 to allow row vector describing the EE of the layers to be extracted as a row vector
%Dr = roofDk(1,:);      %Extract first row of roofDk as row vector Dr

EErPrim = roofDkEE(4,:);       %Extract fourth row of wallDkEE as row vector EEw (MJPrim)

EEr = (EErPrim * PEfact) / 3.6;       %EEs in kWh non-primary

matEEr = EEr./Dr;         %matEEw gives EE per m2 surface area per m depth of each material

rEE = sum((Dr.*matEEr)); %EE (kWh non-primary) of all wall layers per m2 surface area of roof

rEE = rEE + 24.76; %Extra EE (kWh non-prim/m2) for roof sructure and covering

```

A27. winEE


```
% Import WindowsS2 from data library. EEs in MJprimary. 1 kWh = 3.6 MJ. Primary
% energy factor in SBMconstants.m

WtEE = WindowsS2';  %Transpose WindowsS2 to allow row vectors to be extracted
                    %Wee describing the EE per unit of each window type

WeePrim = WtEE(6,:);   %Extract the sixth row of WtEE as row vector Wee (MJprim)

Wee = (WeePrim * PEfact) / 3.6;      %EEs in kWh non-primary

%WtArea = Wh.*Ww.*Wn;                %Row vector describing the total surface area of each window type
%glazArea = sum(WtArea);             %Total surface area of glazing (m^2)
glazEE = sum(Wn.*Wee);              %Total EE of glazing (kWh non-primary)
glazEEsaTot = glazEE / glazArea;       %Glazing EE per m2 surface area, based on initial specification
glazEEsa = glazEEsaTot * GLF;       %GLF in SBMconstants
```

A28. exTemp.m

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```
%Hourly external air temperature.
%Based on monthly average daily max and min temperatures. Order of months
%is [Jan, Feb, ... , Dec]
%Tdmax = [6.8 7.37 9.94 12.6 16.7 19.8 22.1 21.6 18.4 14.3 9.71 7.3];
%%Bath temps
%Tdmin = [2.12 1.77 2.71 3.7 7.23 10.5 12.8 13 10.7 8.09 4.76 2.85];
%%Bath temps

Tdmax = InsolationDataS1(1,:);
Tdmin = InsolationDataS1(2,:);
Tamp = (Tdmax - Tdmin)/2;

n = 1:24;                            %Hours per day. The first hour is 00:00 - 01:00, the second hour is 01:00 - 02:00, etc.
v = -sin(2*pi*((n+2)/24));           %External hourly temperature variation over the day, assuming minimum temperature occurs 03:00 - 04:00, and maximum temperature occurs 15:00 - 16:00
TvHRd = v'*Tamp;                     %Transpose v and multiply by the temperature variation amplitude
b = Tdmin+Tamp;
bb = repmat(b,24,1);                 %repeat row vector b to make a 24-row matrix that can be added to TvHRd
THRd = TvHRd + bb;                   %Matrix of hourly external temperatures. Rows = hours (1-24), columns = months (Jan-Dec)


```

A29. annInsoUni1.m


```
%Programme to produce random hourly insolation incident on a horizontal
%surface (kW/m2) based on three-hourly data at GMT times starting at 00:00

Insol = InsolationData(1:8,:);
InsolationS1 = InsolationData(9,:);
InsolationS2 = InsolationData(10,:);

%Convert insolation at GMT to insolation at local time
TimeShift = floor(abs(LocalTime)/3);

if round(LocalTime/3) > 0
    Insolation = [Insol((8 - TimeShift):8,:) ; Insol(1:(8 - (TimeShift + 1)),:)];
elseif round(LocalTime/3) < 0
    Insolation = [Insol((2 + TimeShift):8,:) ; Insol(1:(TimeShift + 1),:)];
else
    Insolation = Insol;
end;

InsoA = Insolation(1,:);
InsoB = Insolation(2,:);
InsoC = Insolation(3,:);
InsoD = Insolation(4,:);
InsoE = Insolation(5,:);
InsoF = Insolation(6,:);
InsoG = Insolation(7,:);
InsoH = Insolation(8,:);

dayInsoGMT = [repmat(InsoA,3,1);repmat(InsoB,3,1);repmat(InsoC,3,1);repmat(InsoD,3,1);repmat(InsoE,3,1);repmat(InsoF,3,1);repmat(InsoG,3,1);repmat(InsoH,3,1)];
%dayInso is a matrix describing the monthly average hourly insolation
%incident on a horizontal surface. Rows = hours of the day (GMT) 00:00 -
%23:00. Columns = months (Jan - Dec)

%surf(dayInsoGMT)

weekInso = repmat(dayInsoGMT,7,1);
%dayInso repeated seven times to represent hourly insolation over the
%course of a week (00:00 Mon - 23:00 Sun)

Maxdiff = InsolationS1/100;
Mindiff = InsolationS2/100;
%Maxdiff = the imported maximum (%) difference from monthly averaged insolation
Maxdiffs = repmat(Maxdiff,168,1);
Mindiffs = repmat(Mindiff,168,1);
a = weekInso + (weekInso.*Mindiffs);
b = weekInso + (weekInso.*Maxdiffs);

%rand('state',sum(100*clock));
%The random number generator rand can be seeded with the statement
%rand('state',n) where n is any integer.
%The function clock returns the date and time in a six-element vector with
%seconds to two decimal places, so the expression sum(100*clock) never has
%the same value (almost).
x = rand(168,12);

```

```
%In general, you can generate N random numbers in the interval [a,b] with the formula r = a + (b-a).*rand(N,1);.
y = a + (b-a).*x;

randInso = y;

annualInso = ((sum(sum(randInso)))/12)*52; %kWh/m2
% disp(['Annual insolation on a horizontal surface (kWh/m2): ' num2str(annualInso)])

y1 = y(:,1);
y2 = y(:,2);
y3 = y(:,3);
y4 = y(:,4);
y5 = y(:,5);
y6 = y(:,6);
y7 = y(:,7);
y8 = y(:,8);
y9 = y(:,9);
y10 = y(:,10);
y11 = y(:,11);
y12 = y(:,12);
```

A30. PV1.m


```
% Description of PV output

%Area available for PV = a_roof     See thermEnv.m
% disp(['Available PV area (roof) (m2): ' num2str(a_roof)])

%PV EC
PVEC = a_roof * PVec;
% disp(['EC of PV system (kgCO2): ' num2str(PVEC)])
PVEE = a_roof * PVee;
% disp(['EE of PV system (kWh notprimary): ' num2str(PVEE)])

%PVoutDay = a_roof * (cellPower/cellSize) * performanceRatio .* Insolation;
%The hourly output from the PV system for the average day each month

%PVoutWeek = repmat(PVoutDay,7,1);
%The hourly output from the PV system for the average week each month

PVoutWeek = a_roof * (cellPower/cellSize) * performanceRatio .* randInso;
%The random hourly output from the PV system for the average week each month

%disp('Average PV output for each month (Jan - Dec):')
PVmonthly = (sum(PVoutWeek))*4;
%Total PV output for each month (kWh/week * 4)
%disp(PVmonthly)

PVout = ((sum(sum(PVoutWeek)))/12)*52;
% disp(['PV output (kWh/a): ' num2str(PVout)])

% surf(PVoutWeek);
% xlabel('Month of the year (Jan = 1...Dec = 12)');
% ylabel('Hour of the week (00:00 Mon - 23:00 Sun)');
% title('Random PV output (kWh)');
```

A31. domThermal1.m


```
domOcc;
annualTemp1;
annualTemp2;
% buildData;
TotelEnv = sum(elE);        %Average weekly losses through the whole envelope
```

A32. domOcc.m


```
%Description of domestic heating profiles (using the same format as Office
%Occupancy in offOcc.m)

OOmf = [0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0];
% Daily heating pattern Monday to Friday starting at midnight. 1 = heating
% on; 0 = heating off (thermostat assumed to be set)

OOss = [0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0];
% Daily heating pattern Saturday and Sunday starting at
% midnight. 1 = heating on; 0 = heating off (thermostat assumed to be set)

OOw = [repmat(OOmf,1,5) repmat(OOss,1,2)];
% Weekly heating pattern Monday to Sunday starting at
% 00:00 Monday and finishing 23:59 on Sunday. Consists of OOmf repeated
% five times and OOss repeated twice.

hWinter = OOw';

OOwb = OOw ~= 0;
% Weekly pattern (binary). 0 = no heating, 1 = heating on.

OOwbn = OOw == 0;
% Weekly pattern inverse (binary). 1 = no heating, 0 = heating on.

allheating = OOwb + OOwbn;
noheating = allheating ~= 1;

hSummer = noheating';

heatOn = [repmat(hWinter,1,3) repmat(hSummer,1,6) repmat(hWinter,1,3)];
%heatOn is a matrix describing when heating is available (hourly) for the average
%week for each month of the year (twice a day in the winter months, off in
%the summer months). Binary, 1 = heating on; 0 = no heating
```

A33. annualTemp1.m


```
1 %Annual heat losses
2
3 % Heating set points
4 HSP = (OOwb * Tocc) + (OOwbn * Tuno);
5
6 %Hourly external temperature over an average week for each month of the
7 %year. Rows = hours (00:00 Mon - 23:59 Sun), columns = months (Jan - Dec)
8 Thr = repmat(THRd,7,1);
9
10 %Hours when external temperature is above the cooling temp (see constants.m) over an average week for each month of the
11 %year. Rows = hours (00:00 Mon - 23:59 Sun), columns = months (Jan - Dec)
12 Coolhr = Thr >= CoolTemp;
13 CoolingHrs = (sum(sum(Coolhr)))*(52/12);
14 % disp(['No. hours cooling per year: ' num2str(CoolingHrs)])
15
16 %Heat losses through building elements
17 Ehfr = Eu.*Ea.*trf;                          %heat flow rate = U . A . temp reduction factor (1x4 row vector)
18
19 HSPan = repmat(HSP',1,12);
20 %Matrix describing the hourly set point temperature over the average week
21 %for each month of the year (Rows = hours, Columns = month).
22
23 dTan = HSPan - Thr;
24 %Matrix describing the internal-external temperature difference over the
25 %average week for each month of the year (Rows = hours, Columns = month).
26
27 dTanPlus = dTan > 0;        % Heating demand is positive
28 dTanGt = dTan .* dTanPlus;  % Values of positive heating demand
29
30 Gt = (sum(sum(dTanGt))*(52/12))/1000;
31 %Heating degree hours (kKh) based on hourly internal-external temperature
32 %difference over the average week in each month (only when heating demand
33 %is positive)
34 % disp(['Hourly Gt (kKh): ' num2str(Gt)])
35
36 HLvan = (dTan*HLvent)/ifa;
37 %Matrix describing the hourly ventilation heat loss (W/m^2) over the
38 %average week for each month of the year (Rows = hours, Columns = month).
39 elV = sum(HLvan)/1000;      %Average weekly ventilation energy loss (kWh/m2)
40
41 %Heat losses through building elements (W)
42 %Ehfr = Eu.*Ea.*trf;   (see heatLoss.m and line 17 above)      %heat flow rate = U . A . temp reduction factor (1x4 row vector)
43 hlFloor = dTan*Ehfr(1,1);      %Ground floor heat loss matrix
44 hlWall = dTan*Ehfr(1,2);       %External walls heat loss matrix
45 hlGlaz = dTan*Ehfr(1,3);       %Glazing heat loss matrix
46 hlRoof = dTan*Ehfr(1,4);       %Roof heat loss matrix
47 %Matrices describing heat losses through the different building elements.
48 %Heat loss = Heat flow rate x Internal-external temp difference
49
50 %Heat loss through building envelope (W/m2)
51 HLenv = (hlFloor + hlWall + hlGlaz + hlRoof)/ifa;
52
```

```
%Energy loss through building elements (kWh)
elFloor = sum(hlFloor)/1000;        %Average weekly energy loss through the ground↙
floor for each month (1x12 vector)
elWall = sum(hlWall)/1000;          %Average weekly energy loss through the↙
external walls for each month (1x12 vector)
elGlaz = sum(hlGlaz)/1000;          %Average weekly energy loss through the glazing↙
for each month (1x12 vector)
elRoof = sum(hlRoof)/1000;          %Average weekly energy loss through the roof↙
for each month (1x12 vector)

elE = [(elFloor/ifa) ; (elWall/ifa) ; (elGlaz/ifa) ; (elRoof/ifa)];
%Average weekly energy loss (kWh/m2) through building elements. Row 1 =
%Ground floor, Row 2 = External walls, Row 3 = Glazing, Row 4 = Roof.

THL = 52 * ((sum(sum(elE)))/12);
%Total average annual heat loss through the building envelope (kWh/m2a)

%Energy loss (ventilation and conduction) (kWh/m2a)
elEelV = [elE ; elV];           %Matrix describing average weekly energy loss↙
(kWh/m2) through building elements and ventilation for each month
elTot = sum(elEelV);            %Average weekly energy loss for each month (kWh/m2)
elTotAnnual = (sum(elTot)/12)*52;    %Average annual energy loss (kWh/m2a) from↙
ventilation and conduction

```

A34. annualTemp2.m


```
%Annual cooling demand (based on annualTemp1.m)

% Heating set points
%HSP = (OOwb * Tocc) + (OOwbn * Tuno);
% Cooling set points
CSP = (OOwb * CoolTemp) + (OOwbn * CoolTempUno);

%Hourly external temperature over an average week for each month of the
%year. Rows = hours (00:00 Mon - 23:59 Sun), columns = months (Jan - Dec)
%Thr = repmat(THRd,7,1);

%Hours when external temperature is above the cooling temp (see constants.m) over an average week for each month of the
%year. Rows = hours (00:00 Mon - 23:59 Sun), columns = months (Jan - Dec)
%Coolhr = Thr >= CoolTemp;
%CoolingHrs = (sum(sum(Coolhr)))*(52/12);
% disp(['No. hours cooling per year: ' num2str(CoolingHrs)])

%Heat losses through building elements
%Ehfr = Eu.*Ea.*trf;                        %heat flow rate = U . A . temp reduction factor (1x4 row vector)

CSPan = repmat(CSP',1,12);
%Matrix describing the hourly cooling set point temperature over the average week
%for each month of the year (Rows = hours, Columns = month).

CooldTan = CSPan - Thr;
%Matrix describing the internal-external temperature difference (cooling) over the
%average week for each month of the year (Rows = hours, Columns = month).

CHLvan = (CooldTan*HLvent)/ifa;
%Matrix describing the hourly (cooling) ventilation heat loss (W/m^2) over the
%average week for each month of the year (Rows = hours, Columns = month).
CelV = sum(CHLvan)/1000;      %Average weekly ventilation energy loss (kWh/m2)

%Heat losses (cooling) through building elements (W)
%Ehfr = Eu.*Ea.*trf;   (see heatLoss.m)       %heat flow rate = U . A . temp reduction factor (1x4 row vector)
ChlFloor = CooldTan*Ehfr(1,1);       %Ground floor heat loss matrix
ChlWall = CooldTan*Ehfr(1,2);        %External walls heat loss matrix
ChlGlaz = CooldTan*Ehfr(1,3);        %Glazing heat loss matrix
ChlRoof = CooldTan*Ehfr(1,4);        %Roof heat loss matrix
%Matrices describing heat losses through the different building elements.
%Heat loss = Heat flow rate x Internal-external temp difference

%Heat loss (cooling) through building envelope (W/m2)
CHLenv = (ChlFloor + ChlWall + ChlGlaz + ChlRoof)/ifa;

%Energy loss (cooling) through building elements (kWh)
CelFloor = sum(ChlFloor)/1000;        %Average weekly energy loss through the ground floor for each month (1x12 vector)
CelWall = sum(ChlWall)/1000;          %Average weekly energy loss through the external walls for each month (1x12 vector)
CelGlaz = sum(ChlGlaz)/1000;          %Average weekly energy loss through the glazing for each month (1x12 vector)
```

```
CelRoof = sum(ChlRoof)/1000;          %Average weekly energy loss through the roof for each month (1x12 vector)

CelE = [(CelFloor/ifa) ; (CelWall/ifa) ; (CelGlaz/ifa) ; (CelRoof/ifa)];
%Average weekly energy loss (kWh/m2) through building elements. Row 1 =
%Ground floor, Row 2 = External walls, Row 3 = Glazing, Row 4 = Roof.

CoolTHL = 52 * ((sum(sum(CelE)))/12);
%Total average annual heat loss through the building envelope (kWh/m2a)

%Energy loss (ventilation and conduction) (kWh/m2a)
CelEelV = [CelE ; CelV];           %Matrix describing average weekly energy loss (kWh/m2) through building elements and ventilation for each month
CelTot = sum(CelEelV);             %Average weekly energy loss for each month (kWh/m2)
CelTotAnnual = (sum(CelTot)/12)*52;    %Average annual energy loss (kWh/m2a) from ventilation and conduction

```

A35. SBMdomDem.m


```
%Description of Domestic Demand (electricity)

% disp('Household Type');
% disp('1 = Single pensioner')
% disp('2 = Single non-pensioner')
% disp('3 = Multiple pensioner')
% disp('4 = Household with children')
% disp('5 = Household with no children')

h_type = 4; % input('Enter household type:');

DDmfW = WinterWeekday;
% Daily domestic demand hourly percentage of daily total Monday to Friday
% in the winter

hDDmfW = DDmfW * DomesticElectricityprofileS1(h_type,1);
% Household daily demand (hourly per person) Monday to Friday (kWh). Row number of
% matrix defines household type (column number defines day type)
% WINTER

DDssW = WinterWeekend;
% Daily domestic demand hourly percentage of daily total Saturday and
% Sunday in the winter

hDDssW = DDssW * DomesticElectricityprofileS1(h_type,2);
% Household daily demand (hourly per person) Saturday and Sunday (kWh). Row number of
% matrix defines household type (column number defines day type)
% WINTER

DDwW = [repmat(hDDmfW,5,1); repmat(hDDssW,2,1)];
% Weekly winter domestic demand (hourly in kWh) Monday to Sunday starting at
% 00:00 Monday and finishing 23:59 on Sunday. Consists of hDDmfW repeated
% five times and hDDssW repeated twice.


DDmfS = SummerWeekday;
% Daily domestic demand hourly percentage of daily total Monday to Friday
% in the winter

hDDmfS = DDmfS * DomesticElectricityprofileS1(h_type,3);
% Household daily demand (hourly per person) Monday to Friday (kWh). Row number of
% matrix defines household type (column number defines day type)
% SUMMER

DDssS = SummerWeekend;
% Daily domestic demand hourly percentage of daily total Saturday and
% Sunday in the winter

hDDssS = DDssS * DomesticElectricityprofileS1(h_type,4);
% Household daily demand (hourly per person) Saturday and Sunday (kWh). Row number of
% matrix defines household type (column number defines day type)
% SUMMER

```

```
DDwS = [repmat(hDDmfS,5,1); repmat(hDDssS,2,1)];
% Weekly summer domestic demand (hourly in kWh) Monday to Sunday starting at
% 00:00 Monday and finishing 23:59 on Sunday. Consists of hDDmfW repeated
% five times and hDDssW repeated twice.

DDannual = [repmat(DDwW,1,3) repmat(DDwS,1,6) repmat(DDwW,1,3)];
% Weekly electricity demand (hourly in kWh per person) for each month of the year.
% Winter months are defined as Jan, Feb, Mar, Oct, Nov, Dec

totDDpp = ((sum(sum(DDannual)))/12)*52;          %Total annual demand per person
% disp(['Annual domestic electricity demand per person (kWh): ' num2str(totDDpp)]);

if valueOcc == 1
    people = 0; %input('Enter number of occupants:');            %Number of occupants
else
    people = ifa / occDens;                                      %Constant occupant density
end

totDDhouse = totDDpp * people;                   %Total household annual demand
% disp(['Annual household electricity demand (kWh): ' num2str(totDDhouse)]);


% surf(DDannual);
% xlabel('Months of the year (Jan = 1...Dec = 12)');
% ylabel('Hours of the week (Mon am - Sun pm)');
% title('Domestic electricity demand per person (kWh)');


houseDDannual = DDannual * people;
% Weekly electricity demand (hourly in kWh for the household) for each month of the year.
% Winter months are defined as Jan, Feb, Mar, Oct, Nov, Dec

NetDDannual = houseDDannual - PVoutWeek;
%Net household electricity demand (hourly in kWh) for each week of the
%year. (Demand - PV production)

gridDem = (NetDDannual > 0) .* NetDDannual;
% Net demand on grid (hourly) including PV generation
AnnGridDem = (((sum(sum(gridDem)))/12)*52)/ifa;
% Annual demand on grid taking into account hourly demand and PV gen (kWh per m2 ifa).
WeeNetDD = sum(NetDDannual);     %Net demand summed over the week
%WeeGridDem = (WeeNetDD > 0) .* WeeNetDD;



WeeGridDem =  WeeNetDD;
AnnWeeGridDem = ((sum(WeeGridDem)/12)*52)/ifa;
% Annual demand on grid taking into account weekly demand and PV gen (kWh per m2 ifa).

```

```
NettotDDpp = ((sum(sum(NetDDannual)))/12)*52;         %Net total annual demand for the household
% disp(['Net annual domestic electricity household demand (kWh): ' num2str(NettotDDpp)]);

% surf(NetDDannual);
% xlabel('Months of the year (Jan = 1...Dec = 12)');
% ylabel('Hours of the week (Mon am - Sun pm)');
% title('Net household domestic electricity demand (kWh) (Demand - PV production)');
```

A36. domHG1.m


```
%Description of Domestic Heat Gains
%Heat gains from domestic appliances follow the same profile as domestic
%electricity demand as described in domDem.m

%%disp(['Household Type: ' num2str(h_type)]); %see domDem.m for h_type
%%disp('1 = Single pensioner')
%%disp('2 = Single non-pensioner')
%%disp('3 = Multiple pensioner')
%%disp('4 = Household with children')
%%disp('5 = Household with no children')

%DDmfW = WinterWeekday;     see domDem.m
% Daily domestic demand hourly percentage of daily total Monday to Friday
% in the winter

hDHGmfW = DDmfW * DomesticElectricityprofileS2(h_type,1);
% Per person daily heat gains (hourly) Monday to Friday (kWh). Row number of
% matrix defines household type (column number defines day type)
% WINTER

%DDssW = WinterWeekend;     see domDem.m
% Daily domestic demand hourly percentage of daily total Saturday and
% Sunday in the winter

hDHGssW = DDssW * DomesticElectricityprofileS2(h_type,2);
% Per person daily heat gains (hourly) Saturday and Sunday (kWh). Row number of
% matrix defines household type (column number defines day type)
% WINTER

DHGwW = [repmat(hDHGmfW,5,1); repmat(hDHGssW,2,1)];
% Weekly winter domestic heat gains (hourly in kWh) Monday to Sunday starting at
% 00:00 Monday and finishing 23:59 on Sunday. Consists of hDHGmfW repeated
% five times and hDHGssW repeated twice.


%DDmfS = SummerWeekday;     see domDem.m
% Daily domestic demand hourly percentage of daily total Monday to Friday
% in the summer

hDHGmfS = DDmfS * DomesticElectricityprofileS2(h_type,3);
% Per person daily heat gains (hourly) Monday to Friday (kWh). Row number of
% matrix defines household type (column number defines day type)
% SUMMER

%DDssS = SummerWeekend;     see domDem.m
% Daily domestic demand hourly percentage of daily total Saturday and
% Sunday in the summer

hDHGssS = DDssS * DomesticElectricityprofileS2(h_type,4);
% Per person daily demand (hourly) Saturday and Sunday (kWh). Row number of
% matrix defines household type (column number defines day type)
% SUMMER

DHGwS = [repmat(hDHGmfS,5,1); repmat(hDHGssS,2,1)];
% Weekly summer domestic heat gains (hourly in kWh) Monday to Sunday starting at
```

```
% 00:00 Monday and finishing 23:59 on Sunday. Consists of hDHGmfW repeated
% five times and hDHGssW repeated twice.

DHGannual = [repmat(DHGwW,1,3) repmat(DHGwS,1,6) repmat(DHGwW,1,3)];
% Weekly heat gains (hourly in kWh) for each month of the year per person.
% Winter months are defined as Jan, Feb, Mar, Oct, Nov, Dec

totDHGpp = ((sum(sum(DHGannual)))/12)*52;         %Total annual heat gains per person
% disp(['Annual domestic heat gains (from appliances) per person (kWh): ' num2str(totDHGpp)]);

%%disp(['Number of occupants: ' num2str(people)]);            %see domDem.m for people

totDHGhouse = totDHGpp * people;                  %Total household annual heat gains from appliances
% disp(['Annual household heat gains from appliances (kWh): ' num2str(totDHGhouse)]);

%human = 125;        see SBMconstants.m           %Heat gains from a person as in offSpec.m
% disp (['Heat Gains per person (W): ' num2str(human)])
%utilisation = 0.55;  see SBMconstants.m           %Interior heat availability factor in PHPP
weeklyDHGhuman = (human * 24 * 7 * utilisation)/1000;  %Weekly domestic heat gains per person (kWh)

weeklyDHG = ((sum(DHGannual) + weeklyDHGhuman) * people)/ifa;
%Average weekly heat gains for each month of the year (kWh/m2)

totDHGhuman = weeklyDHGhuman * 52;              %Annual heat gains from people per person (kWh)
% disp(['Annual domestic heat gains (from people) per person (kWh): ' num2str(totDHGhuman)]);

totDHGhousehold = totDHGhuman * people;                  %Total household annual heat gains from people
% disp(['Annual household heat gains from people (kWh): ' num2str(totDHGhousehold)]);

TotalDHG = totDHGhouse + totDHGhousehold;
% disp(['Total domestic heat gains (kWh/a): ' num2str(TotalDHG)]);
% disp(['Total domestic heat gains (kWh/m2a): ' num2str(TotalDHG/ifa)]);

% surf(DHGannual);
% xlabel('Months of the year (Jan = 1...Dec = 12)');
% ylabel('Hours of the week (Mon am - Sun pm)');
% title('Domestic heat gains per person from appliances (kWh)');

```

A37. domHeating1.m

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```
% Domestic heating requirement

%Heat gains from people and plug loads
%NP = OOw * people;                                %Number of people in office each hour
%HGplug = ((people - NP)*plugUno) + (NP*plugOcc);  %Heat gains from plug loads in use or on standby (W)
%HGpeop = NP * human;                              %Heat gains from people in office (W)

%HGpp = (HGplug + HGpeop)/ifa;                     %Row vector Heat gains from people and plug loads (W/m^2) every hour over the week


%Heating input required hourly for average week each month
%tranHGpp = HGpp';
%HGppan = repmat(tranHGpp,1,12);     %Heat gains from people and plug loads for average week for each month

HGppan = DHGannual * (1000/ifa) * people;
%DHGannual is the weekly domestic heat gains (hourly in kWh) from appliances per person for each month of the year.
%HGppan is measured in units of W/m2 (for the whole household)

peopleHGmax = repmat(hWinter,1,12);        % see domOcc.m, line 17 for hWinter
%peopleHGmax is a matrix describing when metabolic heat gains are assumed to be at their maximum (hourly over the week for each month of the year).
%The maximum heat gains profile follows the winter heating profile. Binary,
%1 = maximum heat gains; 0 = minimum heat gains
peopleHGmin = peopleHGmax == 0;      % Minimin metabolic heat gains are assumed at all other times. Binary, %1 = maximum heat gains; 0 = minimum heat gains
maxMetHG = peopleHGmax * human * people;     %Maximum metabolic heat gains hourly (W)
minPercentHG = ((sum(allheating) * utilisation) - sum(OOw)) / (sum(allheating) - sum(OOw));      % see domOcc.m for allheating
minMetHG = peopleHGmin * human * minPercentHG * people;     %Minimum metabolic heat gains hourly (W)
MetHG = (maxMetHG + minMetHG) / ifa;         %Matrix describing metabolic heat gains hourly over the week for each month of the year (W/m2)

Hin = HLvan + HLenv - HGppan - MetHG;        %Heating required (W/m2) to maintain internal set point

Heating = Hin > 0;                   %Active heating required when heat losses are greater than 0
absHin = Heating.*Hin;               %Active heating (W/m2) required (ignoring cooling)
actHin = absHin.*heatOn;             %Active heating required and heating available (W/m2) - see domOcc.m, line 30 for heatOn

TotHin = (52*((sum(sum(Hin)))/12))/1000;
TotabsHin = (52*((sum(sum(absHin)))/12))/1000;
TotactHin = (52*((sum(sum(actHin)))/12))/1000;
% disp(['Average annual heating required to maintain HSP (kWh/m2a) (Av HL - Av HG): ' num2str(TotHin)])
```

```
% disp(['Total active heating required to maintain HSP (kWh/m2a) (Hrly HL - Hrly HG): ' num2str(TotabsHin)])
% disp('***The above values do not include heat gains from people (only appliances).***')
% disp(['Total active heating given heating pattern (kWh/m2a): ' num2str(TotactHin)])

% disp('Average weekly gains and losses (kWh/m2) for Jan - Dec:');
% disp(['Envelope losses' '  Ventilation losses' '  Heat gains'])
% disp([TotelEnv' elV' weeklyDHG'])

% surf(absHin);
% xlabel('Months of the year (Jan = 1...Dec = 12)');
% ylabel('Hours of the week (Mon am - Sun pm)');
% title('Heating requirement (W/m2)');

%surf(actHin);
%xlabel('Months of the year (Jan = 1...Dec = 12)');
%ylabel('Hours of the week (Mon am - Sun pm)');
%title('Heating provided (W/m2)');
```

A38. domCooling1.m


```
% Cooling is needed (Coolhr) when the external temperature is above the cooling
% temperature (see SBMonstants.m - default 26 degrees C)
% The hours when cooling is necessary are given by Coolhr (in
% annualTemp1.m)
% The heat energy that needs to be removed is Hin when Hin is negative (see
% domHeating1.m line 29)

%Hin = HLvan + HLenv - HGppan - MetHG;       %Heating required (W/m2) to maintain internal set point
INvan = CHLvan < 0;                          %see annualTemp2.m, line 29 for CHLvan (the hourly (cooling) ventilation heat loss (W/m^2))
ventHin = CHLvan .* INvan;                   %Negative ventilation heat losses (heat gains) compared to cooling set point temp

INenv = CHLenv < 0;                          %see annualTemp2.m, line 44 for CHLenv (Heat loss (cooling) through building envelope (W/m2))
envHin = CHLenv .* INenv;                    %Negative heat losses through the envelope (heat gains) compared to cooling set point temp

CHin = ventHin + envHin - HGppan - MetHG;    %Heat gains: ventilation; conduction; plug; people

Hot = Hin < 0;      % Matrix showing when heat losses are negative
Cooling = -CHin .* Hot .* Coolhr; % Active cooling (W/m2) required - net heat gains are positive, heat losses are negative, and the external temperature is above the cooling set point

% In the ideal Carnot cycle the CoP is inversely proportional to the
% temperature increment, but a real cycle will give 0.82 - 0.93 (average
% 0.85) of the Carnot performance. This will be further reduced by the
% actual component efficiencies such as: electric motor (0.95); compressor
% (0.8); heat exchangers (0.9)
CoP = 0.85 * 0.95 * 0.8 * 0.9;

% Compressor work input = heat removed from source / CoP
CoolWork = Cooling / CoP;

TotCoolWork = (52*((sum(sum(CoolWork)))/12))/1000;    % Annual energy for cooling required (kWh/m2a)
```

A39. SBMZCB.m


```
%Zero Carbon Building Balance
format bank

% disp('Internal floor area of building (m2):');
% disp(ifa)

%Annual ZCB Balance

AnnPVout = PVout / ifa;
% disp(['PV output (kWh/m2a): ' num2str(AnnPVout)]);
%AnnPVoutCO = AnnPVout * elecCI;
AnnPVoutCO = AnnPVout * PVelecCI;        %Elec CI at PV location
% disp(['CO2 from PV output (kgCO2e/m2a): ' num2str(AnnPVoutCO)]);

AnnPVEC = PVEC / (ifa * PVLife);
% disp(['PV EC (kgCO2e/m2a): ' num2str(AnnPVEC)]);
AnnPVEE = PVEE / (ifa * PVLife);
% disp(['PV EE (kWh notprimary/m2a): ' num2str(AnnPVEE)]);
MVHRCO = MVHREC * MVHR;
% disp(['MVHR EC (kgCO2e/m2a): ' num2str(MVHRCO)]);
MVHRee = MVHREE * MVHR; %kWh not primary/m2a);
HEATEC = not(MVHR) * (((Boiler/BoilerLif) + ((BoilerVol * iav)/buildLife))/ifa);
% disp(['Heating system EC (kgCO2e/m2a): ' num2str(HEATEC)]);
HEATee = HEATEC / 0.184;    %kWh/m2a - 0.184 from typcial UK industrial fuel mix as in ICE for PV
%PV storage battery
AnnBattEC = (batteryEC * people) / (ifa * batteryLife);
AnnBattEE = (batteryEE * people) / (ifa * batteryLife);

%PV net CO2 benefit
%PVoutm2PV = (PVout * elecCI)/a_roof;    %PV output per m2 of PV (in kgCO2e/a)
PVoutm2PV = (PVout * PVelecCI)/a_roof;  %Elec CI at PV location
PVECm2PV = PVec / PVLife;               %PV EC per m2 of PV (in kgCO2e/a)
netPVbenefit = PVoutm2PV - PVECm2PV;    %Net benefit of PV (in kgCO2e/a) per m2 of PV
netPVbenefitIFA = netPVbenefit / ifa;   %Net benefit of each m2 of PV per m2 floor area
% disp(['Net PV benefit (kgCO2e/m2a): ' num2str(netPVbenefitIFA)]);
%PV net CO2 benefit

% disp(['Total thermal energy loss (kWh/m2a): ' num2str(elTotAnnual)]);
elTotAnnualCO = elTotAnnual * gasCI;
% disp(['CO2 from thermal energy loss (kgCO2e/m2a): ' num2str(elTotAnnualCO)]);
extraPVtherm = elTotAnnualCO / netPVbenefitIFA;
PVThermBal = extraPVtherm; %for DataPaper3.m
% disp(['PV to balance thermal energy loss (m2): ' num2str(PVThermBal)])

AnnHeatGains = TotalDHG / ifa;
% disp(['Total domestic heat gains (kWh/m2a): ' num2str(AnnHeatGains)]);
AnnHeatGainsCO = AnnHeatGains * gasCI;
% disp(['CO2 from domestic heat gains (kgCO2e/m2a): ' num2str(AnnHeatGainsCO)]);

%absHin = Heating.*Hin;              %Active heating (W/m2) required (ignoring cooling) (see domHeating1.m, line 32)
AnnHeating = (((sum(sum(absHin))/12)*52)/1000);
```

```
% disp(['Total heating required (kWh/m2a): ' num2str(AnnHeating)]);
AnnHeatingCO = AnnHeating * gasCI;
% disp(['CO2 from heating required (kgCO2e/m2a): ' num2str(AnnHeatingCO)]);
%TotCoolWork = (52*((sum(sum(CoolWork)))/12))/1000;    % Annual energy for cooling required (kWh/m2a) (see domCooling1.m, line 30)
% disp(['Total cooling energy required (kWh/m2a): ' num2str(TotCoolWork)]);
AnnCoolingCO = TotCoolWork * elecCI;
% disp(['CO2 from cooling required (kgCO2e/m2a): ' num2str(AnnCoolingCO)]);
AnnElecDem = totDDhouse / ifa;
% disp(['Total domestic electricity demand (kWh/m2a): ' num2str(AnnElecDem)]);
AnnElecDemCO = AnnElecDem * elecCI;
% disp(['CO2 from domestic electricity demand (kgCO2e/m2a): ' num2str(AnnElecDemCO)]);
extraPVelec = AnnElecDemCO / netPVbenefitIFA;
PVElecBal = extraPVelec; %for DataPaper3.m
% disp(['PV to balance electricity demand (m2): ' num2str(PVElecBal)])
AnnEnvEC = EnvEC / (ifa * buildLife);
% disp(['Building envelope EC (kgCO2e/m2a): ' num2str(AnnEnvEC)]);
extraPVbuildEC = AnnEnvEC / netPVbenefitIFA;
% disp(['Extra PV to balance building EC (m2): ' num2str(extraPVbuildEC)])
%Internal building elements
IntWall = f2c * ifa * 0.18;             %surface area of internal walls (m2) assuming 0.18m length of wall per m2 ifa
IntWallEC = IntWall * IntWec;           %(total kgCO2e)
IntWallEE = IntWall * IntWee * PEfact;  %(total kWh non-prim)
IntFloor = (ifa / storeys) * (storeys - 1);    %surface area of intermediate floors (m2)
IntFloorEC = IntFloor * IntFec;         %(total kgCO2e)
IntFloorEE = IntFloor * IntFee * PEfact;
AnnIntEC = (IntWallEC + IntFloorEC) / (ifa * buildLife);   %Internal building elements EC (kgCO2e/m2a)
AnnIntEE = (IntWallEE + IntFloorEE) / (ifa * buildLife);   %Internal building elements EE (kWh/m2a)
%Internal building elements
% disp('Annual Carbon Balance (kgCO2e/m2a):')
%AnnZCB = -AnnPVoutCO + AnnPVEC + elTotAnnualCO - AnnHeatGainsCO + AnnElecDemCO + AnnEnvEC + MVHRCO;
% disp(AnnZCB)
%extraPVAnnZCB = AnnZCB / netPVbenefitIFA;
% disp(['Extra PV needed for annual ZCB (m2): ' num2str(extraPVAnnZCB)])
%Weekly ZCB Balance
% disp(' ')
% disp('*****Weekly ZCB Balance values*****')
WeePVout = sum(PVoutWeek) / ifa;
```

```
% disp(['PV output (kWh/m2w): ' num2str(WeePVout)]);
WeePVoutCO = WeePVout * PVelecCI;
%disp(['CO2 from PV output (kgCO2e/m2w): ' num2str(WeePVoutCO)]);

WeePVEC = PVEC / (ifa * PVLife * 52);
% disp(['PV EC (kgCO2e/m2w): ' num2str(WeePVEC)]);
WeePVEE = AnnPVEE / 52;
% disp(['PV EE (kWh/m2w): ' num2str(WeePVEE)]);
WeeMVHRCO = MVHRCO / 52;
% disp(['MVHR EC (kgCO2e/m2w): ' num2str(WeeMVHRCO)]);
WeeMVHRee = MVHRee / 52;    %kWh/m2w
WeeHEATEC = HEATEC / 52;
% disp(['Heating system EC (kgCO2e/m2w): ' num2str(WeeHEATEC)]);
WeeHEATee = HEATee / 52;

%PV net CO2 benefit weekly
WeePVoutm2PV = (sum(PVoutWeek) * PVelecCI)/a_roof;    %PV output per m2 of PV (in kgCO2e/w)
WeePVECm2PV = PVec / (PVLife * 52);                %PV EC per m2 of PV (in kgCO2e/w)
WeenetPVbenefit = WeePVoutm2PV - WeePVECm2PV;    %Net benefit of PV (in kgCO2e/w)
WeenetPVbenefitIFA = WeenetPVbenefit / ifa;   %Net benefit of PV per m2 floor area weekly
% disp(['Net PV benefit weekly (kgCO2e/m2w): ' num2str(WeenetPVbenefitIFA)]);
%PV net CO2 benefit weekly

%MVHR CO2 benefit weekly
MVHRben = dTan * iav * 0.33 * MVHRdiff;      %dTan = int-ext temp difference (K); iav = internal air volume (m3)
WeeMVHRben = (sum(MVHRben)*gasCI)/(ifa * 1000);     %kgCO2e/m2 average week for each month
AnnMVHRben = 52 * ((sum(WeeMVHRben))/12);           %kgCO2e/m2a
WeenetMVHRben = WeeMVHRben - (repmat(WeeMVHRCO,1,12));  %Weekly net benefit of MVHR per m2 floor area
AnnnetMVHRben = sum(WeenetMVHRben);                 %Annual net benefit of MVHR per m2 floor area
% disp(['Net MVHR benefit weekly (kgCO2e/m2w): ' num2str(WeenetMVHRben)]);
% disp(['Net MVHR benefit annual (kgCO2e/m2a): ' num2str(AnnnetMVHRben)]);
%MVHR CO2 benefit weekly

WeeThermEL = elV + sum(elE);
% disp(['Total thermal energy loss (kWh/m2w): ' num2str(WeeThermEL)]);
WeeThermELCO = WeeThermEL * gasCI;
%disp(['CO2 from thermal energy loss (kgCO2e/m2w): ' num2str(WeeThermELCO)]);
extraPVtherm = WeeThermELCO / netPVbenefitIFA;
% disp(['Extra PV to balance thermal energy loss (m2): ' num2str(extraPVtherm)])

% disp(['Total domestic heat gains (kWh/m2w): ' num2str(weeklyDHG)]);
WeeHeatGainsCO = weeklyDHG * gasCI;
%disp(['CO2 from domestic heat gains (kgCO2/m2w): ' num2str(WeeHeatGainsCO)]);

%absHin = Heating.*Hin;              %Active heating (W/m2) required (ignoring cooling) (see domHeating1.m, line 32)
WeeHeating = sum(absHin) / 1000;
% disp(['Total heating required (kWh/m2w): ' num2str(WeeHeating)]);
```

```
WeeHeatingCO = WeeHeating * gasCI;
% disp(['CO2 from heating required (kgCO2e/m2w): ' num2str(WeeHeatingCO)]);
%TotCoolWork = (52*((sum(sum(CoolWork)))/12))/1000;    % Annual energy for cooling required (kWh/m2a) (see domCooling1.m, line 30)
%CoolWork = Cooling / CoP;
WeeCooling = sum(CoolWork) / 1000;
% disp(['Total cooling energy required (kWh/m2w): ' num2str(WeeCooling)]);
WeeCoolingCO = WeeCooling * elecCI;
% disp(['CO2 from cooling required (kgCO2e/m2w): ' num2str(WeeCoolingCO)]);
WeeElecDem = sum(houseDDannual) / ifa;
% disp(['Total domestic electricity demand (kWh/m2w): ' num2str(WeeElecDem)]);
WeeElecDemCO = WeeElecDem * elecCI;
%disp(['CO2 from domestic electricity demand (kgCO2e/m2w): ' num2str(WeeElecDemCO)]);
extraPVelec = WeeElecDemCO / netPVbenefitIFA;
% disp(['Extra PV to balance electricity demand (m2): ' num2str(extraPVelec)])
WeeEnvEC = (EnvEC + (IntWallEC + IntFloorEC)) / (ifa * buildLife * 52);
% disp(['Building envelope EC (kgCO2e/m2w): ' num2str(WeeEnvEC)]);  +
% internal elements
WeeEnvEE = (AnnEnvEE + AnnIntEE) / 52;
% disp(['Building envelope EE (kWh/m2w): ' num2str(WeeEnvEE)]);    +
% internal elements
extraPVbuildEC = WeeEnvEC / netPVbenefitIFA;
% disp(['Extra PV to balance building EC (m2): ' num2str(extraPVbuildEC)])
% disp('Weekly Carbon Balance (kgCO2e/m2w):')
%WeeZCB = -WeePVoutCO + WeePVEC + WeeThermELCO - WeeHeatGainsCO + WeeElecDemCO + WeeEnvEC + WeeMVHRCO;
if valueBou == 2
    WeeZCB = -WeePVoutCO + WeePVEC + WeeHeatingCO + WeeCoolingCO + WeeElecDemCO + WeeEnvEC + WeeMVHRCO + WeeHEATEC;     %OpC + EC
    WeeZEB = -WeePVout + WeePVEE + WeeHeating + WeeCooling + WeeElecDem + WeeEnvEE + WeeMVHRee + WeeHEATee;     %OpE + EE
elseif valueBou == 1
    WeeZCB = -WeePVoutCO + WeeHeatingCO + WeeCoolingCO + WeeElecDemCO;     %OpC only
    WeeZEB = -WeePVout + WeeHeating + WeeCooling + WeeElecDem;         %OpE only
end
% disp(WeeZCB)
extraPVAnnZCB = WeeZCB / netPVbenefitIFA;
% disp(['Extra PV needed for ZCB (m2) annual basis: ' num2str(extraPVAnnZCB)])
WeeextraPVAnnZCB = WeeZCB ./ WeenetPVbenefitIFA;
% disp(['Extra PV needed for ZCB (m2) weekly basis: ' num2str(WeeextraPVAnnZCB)])
%WeeklyBalance = [-WeePVoutCO; repmat(WeePVEC,1,12); WeeThermELCO; -WeeHeatGainsCO; WeeElecDemCO; repmat(WeeEnvEC,1,12); repmat(WeeMVHRCO,1,12); WeeZCB];
WeeklyBalance = [-WeePVoutCO; repmat(WeePVEC,1,12); WeeHeatingCO; WeeCoolingCO; WeeElecDemCO; repmat(WeeEnvEC,1,12); repmat(WeeMVHRCO,1,12); repmat(WeeHEATEC,1,12); WeeZCB];
```

```
% disp('Weekly Zero Carbon Balance (kgCO2e/m2w) by month (Jan - Dec)')
% disp(['         PV CO' '          PV EC' '         Heat CO' '        Cool CO' ' ElecCO' '         Env EC' '        MVHR CO' '        Heat EC' '        Net CO'])
% disp(WeeklyBalance')

% disp('Annual Carbon Balance (kgCO2e/m2a) from sum of Weekly Carbon Balance')
WeeZCBplus = WeeZCB .* (WeeZCB > 0);
WeeZCBminus = WeeZCB .* (WeeZCB <= 0);
if sum(WeeZCBplus) > 0
    AnnZCBwee = (sum(WeeZCBplus)*52)/12;
else
    AnnZCBwee = (sum(WeeZCBminus)*52)/12;
end

WeeZEBplus = WeeZEB .* (WeeZEB > 0);
WeeZEBminus = WeeZEB .* (WeeZEB <= 0);
if sum(WeeZEBplus) > 0
    AnnZEBwee = (sum(WeeZEBplus)*52)/12;
else
    AnnZEBwee = (sum(WeeZEBminus)*52)/12;
end
%WeeZCBpass = sum(WeeZCB > 0);
%WeeZEBpass = sum(WeeZEB > 0);
% pass is achieved if weekly balance is always zero - in this case WeeZCB
% and WeeZEB will equal 0 and will be counted as zero carbon/energy in the
% simulation (see oneStrun.m lines 10 and 13)

% x = 1:12;
% [ax,p1,p2] = plotyy(x,WeeZCB,x,WeeextraPVAnnZCB);
% xlabel('Month of the year (Jan - Dec)')
% ylabel(ax(1),'Weekly Average Zero Carbon Balance (kgCO2/m2)')
% ylabel(ax(2),'Extra PV required to achieve zero carbon (m2)')
% ylim(ax(2),[-(5*a_roof) (10*a_roof)]);
% ax(2).YTick = -500:50:500;

% disp('Annual Carbon Balance (kgCO2e/m2a):')
%AnnZCB = sum(WeeZCB);
%AnnZCB = -AnnPVoutCO + AnnPVEC + ((TotabsHin - (totDHGhousehold/ifa))*gasCI) + AnnElecDemCO + AnnEnvEC + MVHRCO;    %hourly heating
%AnnZCB = -AnnPVoutCO + elTotAnnualCO - AnnHeatGainsCO + AnnElecDemCO;
%AnnZCB = ifa;
%AnnZCB = AnnPVEC + elTotAnnualCO - AnnHeatGainsCO + (AnnGridDem * elecCI) + AnnEnvEC + MVHRCO;      %Electricity hour
%AnnZCB = AnnPVEC + elTotAnnualCO - AnnHeatGainsCO + (AnnWeeGridDem * elecCI) + AnnEnvEC + MVHRCO;  %Electricity Week
%AnnZCB = -AnnPVoutCO + AnnPVEC + ((TotactHin - (totDHGhousehold/ifa))*gasCI) + AnnElecDemCO + AnnEnvEC + MVHRCO;    %On demand heating

%AnnZCB = AnnPVEC + ((TotabsHin - (totDHGhousehold/ifa))*gasCI) + (AnnGridDem * elecCI) + AnnEnvEC + MVHRCO;      %Electricity hour/Heat hour
%AnnZCB = AnnPVEC + ((TotabsHin - (totDHGhousehold/ifa))*gasCI) + (AnnWeeGridDem * elecCI) + AnnEnvEC + MVHRCO;  %Electricity Week/Heat hour

%AnnZCB = AnnWeeklyCO;   %see SBM.m lines 27 - 33

```

```
%Hourly heating + cooling where necessary
if valueBou == 2
    %AnnZCBoriginal = -AnnPVoutCO + AnnPVEC + (TotabsHin * gasCI) + (TotCoolWork * elecCI) + AnnElecDemCO + AnnEnvEC + AnnIntEC + MVHRCO + HEATEC + AnnBattEC;    %hourly heating
    AnnZCBoriginal = AnnEnvEC + AnnIntEC + MVHRCO + HEATEC + AnnBattEC;    % EnvelopeEC AnnPVEC; %
    %AnnZEBoriginal = -AnnPVout + AnnPVEE + TotabsHin + TotCoolWork + AnnElecDem + AnnEnvEE + AnnIntEE + MVHRee + HEATee + AnnBattEE;          %EE with hourly heating
    AnnZEBoriginal = AnnEnvEE + AnnIntEE + MVHRee + HEATee + AnnBattEE;          % EnvelopEE AnnPVEE; %
elseif valueBou == 1
    AnnZCBoriginal = -AnnPVoutCO + (TotabsHin * gasCI) + (TotCoolWork * elecCI) + AnnElecDemCO;    %No EC
    AnnZEBoriginal = -AnnPVout + TotabsHin + TotCoolWork + AnnElecDem; %No EE
end

%Embodied energy (kWh non-primary)
%AnnZEB = -AnnPVout + AnnPVEE + elTotAnnual + (TotabsHin - (totDHGhousehold/ifa)) + TotCoolWork + AnnElecDem + AnnEnvEE;          %EE with hourly heating
%WRONG! Heat loss counted twice! ***** AnnZEB = -AnnPVout + elTotAnnual + (TotabsHin - (totDHGhousehold/ifa)) + TotCoolWork + AnnElecDem; %No EE

if valueBal == 1
    AnnZCB = AnnZCBoriginal;
    AnnZEB = AnnZEBoriginal;
elseif valueBal == 2
    AnnZCB = AnnZCBwee;
    AnnZEB = AnnZEBwee;
end

%AnnZCB = (sum(elE(3,:)) / 12) * 52;
%AnnZEB = (sum(elV) / 12) * 52;

%AnnZCB = AnnElecDemCO - AnnPVoutCO;
%AnnZEB = AnnElecDem - AnnPVout;
```

A40. Example SBM output for a typical house-sized building – PV located onsite

Athens (Brick)


```
>> load('TraditionalDomesticWatfordEE.mat')
>> logDataExample
1 - Location: Athens = 1, Carcassonne = 2, Macapa = 3, Mumbai = 4, Oslo = 5, Seattle = 6
Enter location value: 1
2 - Material: Brick = 1, Straw Seq = 2, Straw exSeq = 3
Enter material value: 1
3 - Boundary: Operational only = 1, Operational+Embodied = 2
Enter boundary value: 2
4 - Balance Period: Annual = 1, Monthly = 2
Enter balance period value: 1
5 - PV Location: Onsite = 1, Remote = 2
Enter PV location value: 1
6 - Infiltration: 0.6ach+MVHR = 1, 10ach+MVHR = 2, 30m3 = 3
Enter infiltration value: 1
7 - Occupant Density: No people = 1, 35m2/p = 2, 20m2/p = 3
Enter occupant density value: 2
8 - PV Specification: LowE = 1, HighE = 2
Enter PV specification value: 1
OpE (kWh/m2a): 60.8803
OpC (kgCO2e/m2a): 52.4508
PV gen. (kWh/m2a): 99.1761
PV gen. (kgCO2e/m2a): 86.8783
Internal floor area of building (m2):
         73.15

PV output (kWh/m2a): 99.1761
CO2 from PV output (kgCO2e/m2a): 86.8783
PV EC (kgCO2e/m2a): 3.0552
PV EE (kWh notprimary/m2a): 4.9416
MVHR EC (kgCO2e/m2a): 3.3
Heating system EC (kgCO2e/m2a): 0
Net PV benefit (kgCO2e/m2PVa): 136.2661
Total thermal energy loss (kWh/m2a): -38.893
CO2 from thermal energy loss (kgCO2e/m2a): -8.4009
PV to balance thermal energy loss (m2): -4.51
Total domestic heat gains (kWh/m2a): 48.8803
```

```
CO2 from domestic heat gains (kgCO2e/m2a): 10.5581
Total heating required (kWh/m2a): 1.3339
CO2 from heating required (kgCO2e/m2a): 0.28811
Total cooling energy required (kWh/m2a): 21.5926
CO2 from cooling required (kgCO2e/m2a): 18.9151
Total domestic electricity demand (kWh/m2a): 37.9538
CO2 from domestic electricity demand (kgCO2e/m2a): 33.2476
PV to balance electricity demand (m2): 17.8488
Building envelope EC (kgCO2e/m2a): 4.26
Extra PV to balance building EC (m2): 0.048996

*****Weekly ZCB Balance values*****
PV output (kWh/m2w): 1.2685      1.4626      1.7287       2.089      2.3658      2.4251      2.5538      2.5524      2.3236
1.7656      1.2712      1.0806
CO2 from PV output (kgCO2e/m2w): 1.1112      1.2812      1.5143      1.8299      2.0724      2.1243      2.2371      2.2359
2.0355      1.5467      1.1136     0.94661
PV EC (kgCO2e/m2w): 0.058754
MVHR EC (kgCO2e/m2w): 0.063462
Heating system EC (kgCO2e/m2w): 0
Net PV benefit weekly (kgCO2e/m2PVw): 1.7108      1.9873      2.3662      2.8793      3.2735      3.3579      3.5412      3.5392
3.2134      2.4189      1.7148      1.4433
Net MVHR benefit weekly (kgCO2e/m2w): -0.025925   -0.024493   -0.042507   -0.076779    -0.12251    -0.16546    -0.18763
-0.18671    -0.15623    -0.11604   -0.071699   -0.037611
Net MVHR benefit annual (kgCO2e/m2a): -1.2136
Total thermal energy loss (kWh/m2w): 0.74527      0.7737     0.41604    -0.26442     -1.1723     -2.0252     -2.4654      -2.447
-1.8418     -1.0439    -0.16354     0.51325
CO2 from thermal energy loss (kgCO2e/m2w): 0.16098     0.16712    0.089865   -0.057115    -0.25322    -0.43744    -0.53252
-0.52856    -0.39782    -0.22549   -0.035325     0.11086
Extra PV to balance thermal energy loss (m2): 0.08642    0.089717    0.048244   -0.030662    -0.13594    -0.23484    -0.28588
-0.28375    -0.21357    -0.12105   -0.018964    0.059516
Total domestic heat gains (kWh/m2w): 1.0513      1.0513      1.0513     0.82875     0.82875     0.82875     0.82875     0.82875
0.82875      1.0513      1.0513      1.0513
CO2 from domestic heat gains (kgCO2e/m2w): 0.22707     0.22707     0.22707     0.17901     0.17901     0.17901     0.17901
0.17901     0.17901     0.22707     0.22707     0.22707
Total heating required (kWh/m2w): 0.10243     0.11313    0.043253           0           0           0           0           0
0           0           0    0.048998
```

```
CO2 from heating required (kgCO2e/m2w): 0.022124    0.024437   0.0093427          0           0           0           0
0           0           0           0    0.010583
Total cooling energy required (kWh/m2w): 0           0           0           0           0     0.97984      1.5798      1.6439
0.77943           0           0           0
CO2 from cooling required (kgCO2e/m2w): 0           0           0           0           0     0.85834      1.3839        1.44
0.68278           0           0           0
Total domestic electricity demand (kWh/m2w): 0.863       0.863       0.863     0.59676     0.59676     0.59676     0.59676
0.59676     0.59676       0.863       0.863       0.863
CO2 from domestic electricity demand (kgCO2e/m2w): 0.75599     0.75599     0.75599     0.52276     0.52276     0.52276
0.52276     0.52276     0.52276     0.75599     0.75599     0.75599
Extra PV to balance electricity demand (m2): 0.40585     0.40585     0.40585     0.28064     0.28064     0.28064     0.28064
0.28064     0.28064     0.40585     0.40585     0.40585
Building envelope EC (kgCO2e/m2w): 0.091266
Extra PV to balance building EC (m2): 0.048996
Weekly Carbon Balance (kgCO2e/m2w):
  Columns 1 through 9

        -0.12         -0.29         -0.54         -1.09         -1.34         -0.53         -0.12         -0.06         -0.62

  Columns 10 through 12

        -0.58         -0.14          0.03

Extra PV needed for ZCB (m2) annual basis: -0.064192    -0.15425    -0.28749    -0.58715    -0.71733     -0.2844   -0.062793
-0.032001    -0.33094    -0.30988   -0.077379    0.017954
Extra PV needed for ZCB (m2) weekly basis: -5.11281     -10.5768     -16.5559     -27.7872     -29.8601     -11.5411
-2.41627     -1.23208     -14.0334     -17.4571     -6.14888      1.69504
Weekly Zero Carbon Balance (kgCO2e/m2w) by month (Jan - Dec)
        PV CO          PV EC         Heat CO         Cool CO     ElecCO        Env EC        MVHR CO        Heat EC       Net CO
        -1.11          0.06          0.02              0          0.76          0.09          0.06              0         -0.12
        -1.28          0.06          0.02              0          0.76          0.09          0.06              0         -0.29
        -1.51          0.06          0.01              0          0.76          0.09          0.06              0         -0.54
        -1.83          0.06             0              0          0.52          0.09          0.06              0         -1.09
        -2.07          0.06             0              0          0.52          0.09          0.06              0         -1.34
        -2.12          0.06             0           0.86          0.52          0.09          0.06              0         -0.53
        -2.24          0.06             0           1.38          0.52          0.09          0.06              0         -0.12
```

```
       -2.24        0.06           0        1.44        0.52        0.09        0.06           0       -0.06
       -2.04        0.06           0        0.68        0.52        0.09        0.06           0       -0.62
       -1.55        0.06           0           0        0.76        0.09        0.06           0       -0.58
       -1.11        0.06           0           0        0.76        0.09        0.06           0       -0.14
       -0.95        0.06        0.01           0        0.76        0.09        0.06           0        0.03

Annual Carbon Balance (kgCO2e/m2a) from sum of Weekly Carbon Balance
        0.14

Annual Carbon Balance (kgCO2e/m2a):
        8.05

Annual Energy Balance (kWh/m2a):
       13.94

Annual Insolation (kWh/m2a)

ans =

     1730.54

Average temperature (deg. C)

ans =

       18.54

Annual infiltration losses (kWh/m2a)

ans =

       -2.24

Example ZCB data
        1.00        1.00        2.00        1.00        1.00        1.00        2.00        1.00        8.05
```

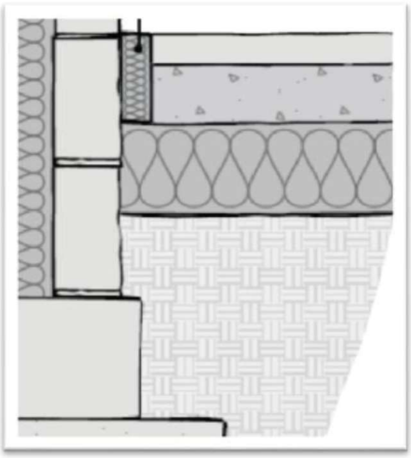
```
Example ZEB data
         1.00          1.00          2.00          1.00          1.00          1.00          2.00          1.00         13.94

***** RENAME DATARUNS *****
suffix: 1  1  2  1  1  1  2  1
>>
```

A42. Ground floor construction data

Data imported to the Standard Building Model:

	Depth (m)	k(W/mK)	ECe per m2 (kgCO2e)	EE per m2 (MJprim)
Concrete (general) 28/35 MPa	0.19	1.3	45.6	311.6
Expanded Polystyrene	0.185	0.035	15.21625	409.8
High Density Polyethylene (HDPE) Resin	0.001	0.5	1.8914	75.2
Sand	0.05	2	0.561	8.9
General aggregate (gravel or crushed rock)	0.6	1.3	6.9888	111.6

Accompanying notes:



Concrete
Construction U-Value = 0.10 W/m2K
SAP reference values for England and Wales assumes ground floor U = 0.13 W/m2K

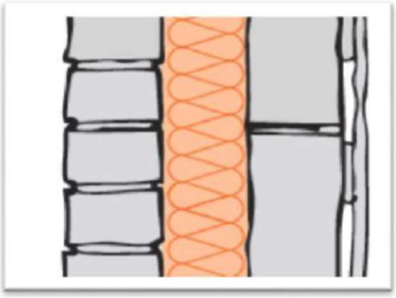
Illustration from Thermal Bridging Buide (Zero Carbon Hub,

A43. Brick walls construction data

Data imported to the Standard Building Model:

	Depth (m)	k(W/mK)	ECe per m2 (kgCO2e)	EE per m2 (MJprim)
Brick	0.1025	0.84	46.1	575.9
Polyurethane Rigid Foam	0.1	0.023	12.8	304.5
Concrete Block - 8 MPa Compressive Strength	0.1	0.19	3.8	35.4
Plasterboard	0.0125	0.25	3.9	67.5

Accompanying notes:



Brick and block wall. Calculations assume no cavity.
Construction U-Value = 0.19 W/m2K
SAP reference values for England and Wales assumes external walls U = 0.18 W/m2K

Illustrations from Builders' Book (Zero Carbon Hub, 2015)

A44. Straw walls construction data

Data imported to the Standard Building Model:

	Depth (m)	k(W/mK)	ECe per m2 (kgCO2e)	EE per m2 (MJprim)
Straw Bale	0.4	0.072	-216.5	778.62

Accompanying notes:

Straw Bale.
Construction U-Value = 0.16 W/m2K
SAP reference values for England and Wales assumes external walls U = 0.18 W/m2K

GF cell dimensions = 0.4 x 1 x 4m
GF cell EC = -219.78 kgCO2/m2(surface area)
FF cell dimensions = 0.4 x 1 x 3.7m
FF cell EC = -213.12 kgCO2/m2(surface area)

Timber EE = 12 MJ(prim)/kg
Straw EE = 0 MJ (??)

The embodied carbon per straw bale is calculated as (including sequestration):
-216.45 kgCO2/m2(surface area)

Illustration from Structural development and testing of a prototype house using timber and straw bales (Maskell et al. 2014)
Also:
* k (straw bales) = 0.052 - 0.080 W/mK
* ModCell panels are typically formed using a softwood glulam timber frame (C24 grade) and measure 3.20m by 2.6 - 2.9m high and 0.48 - 0.49m thick)

A45. Roof construction data

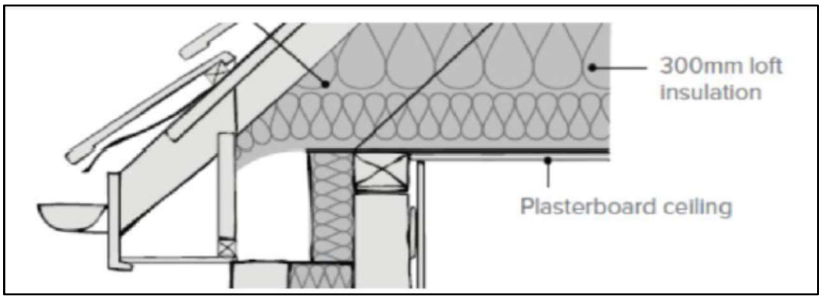
Data imported to the Standard Building Model:

	Depth (m)	k(W/mK)	ECe per m2 (kgCO2e)	EE per m2 (MJprim)
MineralWool	0.3	0.036	11.52	149.4
Plasterboard	0.0125	0.25	3.9	67.5

Accompanying notes:

Mineral Wool
Construction U-Value = 0.12 W/m2K
SAP reference values for England and Wales assumes roof U = 0.13 W/m2K

Illustration from Thermal Bridging Guide (Zero Carbon Hub, 2016)



A46. PVC windows data

Data imported to the Standard Building Model:

	Height (m)	Width (m)	Number	U-value (W/m2K)	ECe per unit (kgCO2)	EE per unit (MJprim)
Double PVC	1.2	1.2	20	1.4	125	2470

Accompanying notes:

Embodied carbon for 1.2mx1.2m Double Glazed (Air or Argon Filled) ($kgCO_2$/unit):
* Aluminium Framed 279
* PVC Framed 110 to 126   EE = 2,150 to 2,470 MJprim per unit
* Aluminium -Clad Timber Framed 48 to 75
* Timber Framed 12 to 25

"...the full CO_2e is approximately 6% higher than the CO_2 only value of embodied carbon. This is for the average mixture of fuels used in the UK industry."
ICE V2.0

SAP reference values for England and Wales assumes windows U = 1.4 W/m2K

A47. Location temperature data[25]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oslo	Tdmax	-1.38	-0.53	2.8	7.46	13.7	17.4	19.7	18.5	13.4	7.95	2.25	-0.65
Oslo	Tdmin	-7.25	-7.12	-4.71	-0.51	4.51	8.52	10.7	10.2	6.29	2.68	-2.22	-5.84
Seattle	Tdmax	6.26	7.31	9.31	11.8	15.4	18.5	22.2	22.5	19.7	13.9	8.49	5.82
Seattle	Tdmin	0.39	-0.18	0.63	1.91	4.24	6.41	8.86	9.78	8.25	5.05	2.1	-0.03
Carcassonr	Tdmax	8.38	9.76	13	15.5	20.7	24.9	27.7	27.3	22.9	17.9	12	9.23
Carcassonr	Tdmin	1.43	1.91	3.66	5.64	9.69	13.2	15.9	15.9	12.5	9.86	5.16	2.7
Athens	Tdmax	13.3	13.3	15.4	19.4	24.4	29	31.3	31	27.6	23.1	18.1	14.4
Athens	Tdmin	7.49	7.18	8.98	12.4	17.3	22	24.5	24.6	21.4	17.2	12.6	8.92
Mumbai	Tdmax	26.2	25.8	26.6	27.3	28.3	28.5	28	27.3	27.4	29	29.1	27.7
Mumbai	Tdmin	23.9	23.4	24.3	25.1	26.2	26.9	26.6	25.9	25.7	27	26.8	25.2
Macapa	Tdmax	28.5	28.1	28.1	28.3	28.7	28.7	29	29.6	30.6	31.1	30.7	29.8
Macapa	Tdmin	22.3	22.2	22.4	22.6	22.6	22	21.6	21.5	22	22.7	22.8	22.8
Accra	Tdmax	27.9	27.9	28	28.1	27.9	26.8	25.7	25.3	25.8	26.6	27.3	27.7
Accra	Tdmin	23.8	24.1	24.5	24.8	24.8	24.1	23	22.5	23	23.6	24	24

[25] Data source:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

A48. Location insolation data[26]

Data imported to the Standard Building Model:

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oslo	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Oslo	Average@03	#VALUE!	#VALUE!	#VALUE!	0	0.018722	0.03444	0.017858	0	0	#VALUE!	#VALUE!	#VALUE!
Oslo	Average@06	#VALUE!	0	0.055584	0.142297	0.224662	0.206643	0.205372	0.152837	0.089275	0.032769	0	#VALUE!
Oslo	Average@09	0.072308	0.20587156	0.31961	0.383108	0.439962	0.404675	0.410744	0.397376	0.357101	0.245769	0.165926	0.06
Oslo	Average@12	0.192821	0.336880734	0.430779	0.448784	0.486767	0.447726	0.482178	0.4687	0.433623	0.311308	0.237037	0.15
Oslo	Average@15	0.024103	0.112293578	0.236234	0.284595	0.336992	0.327184	0.34824	0.305674	0.229565	0.098308	0.023704	0
Oslo	Average@18	#VALUE!	0	0	0.032838	0.093609	0.120542	0.11608	0.061135	0.012754	0	#VALUE!	#VALUE!
Oslo	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Oslo	MaxDiff	21	28	20	16	18	24	19	28	20	26	13	17
Oslo	MinDiff	-18	-28	-24	-15	-17	-20	-17	-17	-21	-38	-20	-13
Seattle	Average@00	0.076577	0.157704082	0.238384	0.28688	0.312008	0.339563	0.383771	0.378547	0.30237	0.15	0.06254	0.04883
Seattle	Average@03	#VALUE!	0	0	0.020491	0.045884	0.069654	0.071399	0.039847	0.01163	0	#VALUE!	#VALUE!
Seattle	Average@06	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Seattle	Average@09	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Seattle	Average@12	#VALUE!	#VALUE!	#VALUE!	0	0	0.008707	0.008925	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Seattle	Average@15	0	0.014336735	0.059596	0.133194	0.183534	0.200255	0.205273	0.16935	0.127926	0.054545	0.015635	0
Seattle	Average@18	0.183784	0.301071429	0.369495	0.420074	0.431305	0.435337	0.47302	0.498088	0.500074	0.368182	0.250159	0.179043
Seattle	Average@21	0.3	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.4	0.3	0.3
Seattle	MaxDiff	27.0	22.0	27.0	22.0	25.0	21.0	22.0	13.0	17.0	28.0	27.0	19.0
Seattle	MinDiff	-17.0	-29.0	-20.0	-15.0	-14.0	-15.0	-30.0	-17.0	-14.0	-13.0	-17.0	-17.0
Carcassonr	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Carcassonr	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Carcassonr	Average@06	0	0	0.036826	0.071935	0.119228	0.130612	0.11586	0.098905	0.057783	0.027231	0	0
Carcassonr	Average@09	0.206842	0.286440678	0.392809	0.400783	0.431055	0.426667	0.463442	0.474745	0.450708	0.354	0.255215	0.200388
Carcassonr	Average@12	0.430921	0.501271186	0.589213	0.544654	0.550282	0.557279	0.614951	0.642883	0.624057	0.490154	0.414724	0.400775
Carcassonr	Average@15	0.206842	0.286440678	0.380534	0.369954	0.394369	0.417959	0.463442	0.464854	0.404481	0.272308	0.159509	0.145736
Carcassonr	Average@18	0	0.014322034	0.024551	0.051382	0.082542	0.113197	0.11586	0.079124	0.03467	0	0	#VALUE!
Carcassonr	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Carcassonr	MaxDiff	24	28	29	33	17	17	12	13	16	18	25	24
Carcassonr	MinDiff	-26	-16	-26	-22	-18	-19	-20	-14	-11	-32	-20	-29
Athens	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Athens	Average@03	#VALUE!	#VALUE!	0	0	0.009191	0.017399	0.008913	0.009819	0	0	#VALUE!	#VALUE!
Athens	Average@06	0.061308	0.091145833	0.16275	0.285736	0.330886	0.365389	0.347609	0.314199	0.271324	0.182733	0.100183	0.061734
Athens	Average@09	0.459813	0.494791667	0.58125	0.6327	0.661773	0.713378	0.721957	0.756042	0.734837	0.626512	0.472294	0.401272
Athens	Average@12	0.459813	0.494791667	0.569625	0.602086	0.615816	0.669879	0.686304	0.716767	0.667006	0.535145	0.400734	0.370405
Athens	Average@15	0.076636	0.130208333	0.186	0.234711	0.257356	0.32189	0.329783	0.304381	0.226104	0.104419	0.042936	0.030867
Athens	Average@18	#VALUE!	#VALUE!	0	0	0.009191	0.017399	0.017826	0.009819	0	#VALUE!	#VALUE!	#VALUE!
Athens	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Athens	MaxDiff	26	22	26	14	16	7	8	7	14	19	23	28
Athens	MinDiff	-32	-21	-31	-17	-9	-16	-10	-9	-13	-19	-21	-24
Mumbai	Average@00	#VALUE!	#VALUE!	0	0	0.009168	0.009982	0	0	0	0	0	#VALUE!

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

From NASA https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

26 Data source:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Data imported to the Standard Building Model:

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mumbai	Average@03	0.245865	0.275328	0.337248	0.367642	0.366712	0.279504	0.23712	0.227344	0.281982	0.340892	0.336208	0.26972
Mumbai	Average@06	0.860526	0.906288	0.916894	0.880407	0.806767	0.688777	0.60268	0.60625	0.735168	0.835734	0.88855	0.84594
Mumbai	Average@09	0.823647	0.883344	0.874738	0.812683	0.742592	0.628883	0.55328	0.558887	0.654602	0.725769	0.744461	0.7356
Mumbai	Average@12	0.184398	0.240912	0.263475	0.24187	0.247531	0.209628	0.18772	0.161035	0.161133	0.131958	0.108067	0.1226
Mumbai	Average@15	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Mumbai	Average@18	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Mumbai	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Mumbai	MaxDiff	3	3	3	4	5	13	16	12	12	7	5	4
Mumbai	MinDiff	-3	-3	-5	-4	-9	-10	-15	-18	-16	-11	-6	-8
Macapa	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Macapa	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Macapa	Average@06	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Macapa	Average@09	0.009862	0.009858824	0.00986	0.00986	0.019722	0.009891	0.00988	0.009872	0.019733	0.029593	0.029613	0.019793
Macapa	Average@12	0.325459	0.305623529	0.305674	0.335245	0.355	0.375861	0.39521	0.43439	0.483456	0.503073	0.46393	0.385971
Macapa	Average@15	0.581881	0.552094118	0.581767	0.591608	0.562083	0.603355	0.652096	0.71082	0.779449	0.769406	0.710701	0.643285
Macapa	Average@18	0.424083	0.414070588	0.424	0.374685	0.384583	0.425316	0.474251	0.533115	0.552521	0.532666	0.493542	0.455248
Macapa	Average@21	0.059174	0.059152941	0.059163	0.039441	0.039444	0.049455	0.059281	0.069107	0.059199	0.049321	0.039483	0.049483
Macapa	MaxDiff	11	12	12	15	12	11	9	7	7	7	11	11
Macapa	MinDiff	-14	-12	-11	-11	-12	-11	-9	-8	-8	-6	-13	-12
Accra	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Accra	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Accra	Average@06	0.020458	0.020185185	0.019852	0.029664	0.039759	0.029865	0.029869	0.029662	0.029598	0.040081	0.040719	0.030775
Accra	Average@09	0.40916	0.413796296	0.436747	0.464739	0.437344	0.36833	0.358428	0.355946	0.384777	0.450909	0.468263	0.441113
Accra	Average@12	0.746718	0.756944444	0.734529	0.71194	0.675895	0.607246	0.627249	0.583356	0.5525	0.681374	0.712575	0.718091
Accra	Average@15	0.51145	0.524814815	0.506229	0.464739	0.417465	0.378284	0.418166	0.41527	0.424241	0.410828	0.407186	0.46163
Accra	Average@18	0.040916	0.04037037	0.039704	0.029664	0.029819	0.029865	0.039825	0.03955	0.029598	0.02004	0.020359	0.020517
Accra	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Accra	MaxDiff	8	3	7	6	11	10	17	11	10	6	8	4
Accra	MinDiff	-8	-5	-7	-5	-7	-9	-15	-11	-12	-6	-6	-4

Oslo Insolation data[27]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Oslo	Average@00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Oslo	Average@03	n/a	n/a	n/a	0	0.02	0.04	0.02	0	0	n/a	n/a	n/a	
Oslo	Average@06	n/a	0	0.04	0.13	0.24	0.24	0.23	0.15	0.07	0.02	0	n/a	
Oslo	Average@09	0.03	0.11	0.23	0.35	0.47	0.47	0.46	0.39	0.28	0.15	0.07	0.02	
Oslo	Average@12	0.08	0.18	0.31	0.41	0.52	0.52	0.54	0.46	0.34	0.19	0.1	0.05	
Oslo	Average@15	0.01	0.06	0.17	0.26	0.36	0.38	0.39	0.3	0.18	0.06	0.01	0	
Oslo	Average@18	n/a	0	0	0.03	0.1	0.14	0.13	0.06	0.01	0	n/a	n/a	
Oslo	Average@21	n/a	n/a	n/a	n/a	0	0	0	0	n/a	n/a	n/a	n/a	
Oslo	MaxDiff	21	28	20	16	18	24	19	28	20	26	13	17	
Oslo	MinDiff	-18	-28	-24	-15	-17	-20	-17	-17	-21	-38	-20	-13	
Oslo	Daily Av Horz	0.39	1.09	2.31	3.7	5.32	5.54	5.51	4.23	2.76	1.3	0.54	0.24	2.75
Oslo	Daily Av 59de	0.94	2.04	3.21	4.05	4.98	4.77	4.92	4.31	3.52	2.13	1.28	0.72	3.08
Oslo	Daily Av Opt /	0.97	2.06	3.22	4.26	5.65	5.71	5.74	4.67	3.56	2.13	1.31	0.75	3.34
Oslo	Opt Ang	75	67	53	37	23	14	17	30	48	62	74	78	48
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	59 deg	2.4	1.9	1.4	1.1	0.9	0.9	0.9	1.0	1.3	1.6	2.4	3.0	
	Opt Ang	2.5	1.9	1.4	1.2	1.1	1.0	1.0	1.1	1.3	1.6	2.4	3.1	
59 deg														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Oslo	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Oslo	Average@03	#VALUE!	#VALUE!	#VALUE!	0	0.018722	0.03444	0.017858	0	0	#VALUE!	#VALUE!	#VALUE!	
Oslo	Average@06	#VALUE!	0	0.055584	0.142297	0.224662	0.206643	0.205372	0.152837	0.089275	0.032769	0	#VALUE!	
Oslo	Average@09	0.072308	0.20587156	0.31961	0.383108	0.439962	0.404675	0.410744	0.397376	0.357101	0.245769	0.165926	0.06	
Oslo	Average@12	0.192821	0.336880734	0.430779	0.448784	0.486767	0.447726	0.482178	0.4687	0.433623	0.311308	0.237037	0.15	
Oslo	Average@15	0.024103	0.112293578	0.236234	0.284595	0.336992	0.327184	0.34824	0.305674	0.229565	0.098308	0.023704	0	
Oslo	Average@18	#VALUE!	0	0	0.032838	0.093609	0.120542	0.11608	0.061135	0.012754	0	#VALUE!	#VALUE!	
Oslo	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Oslo	MaxDiff	21	28	20	16	18	24	19	28	20	26	13	17	
Oslo	MinDiff	-18	-28	-24	-15	-17	-20	-17	-17	-21	-38	-20	-13	
Opt Ang														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Oslo	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Oslo	Average@03	#VALUE!	#VALUE!	#VALUE!	0	0.021241	0.041227	0.020835	0	0	#VALUE!	#VALUE!	#VALUE!	
Oslo	Average@06	#VALUE!	0	0.055758	0.149676	0.254887	0.247365	0.239601	0.165603	0.09029	0.032769	0	#VALUE!	
Oslo	Average@09	0.074615	0.207889908	0.320606	0.402973	0.499154	0.484422	0.479201	0.430567	0.361159	0.245769	0.169815	0.0625	
Oslo	Average@12	0.198974	0.340183486	0.432121	0.472054	0.552256	0.535957	0.562541	0.507849	0.438551	0.311308	0.242593	0.15625	
Oslo	Average@15	0.024872	0.113394495	0.23697	0.299351	0.382331	0.391661	0.406279	0.331206	0.232174	0.098308	0.024259	0	
Oslo	Average@18	#VALUE!	0	0	0.034541	0.106203	0.144296	0.135426	0.066241	0.012899	0	#VALUE!	#VALUE!	
Oslo	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Oslo	MaxDiff	21	28	20	16	18	24	19	28	20	26	13	17	
Oslo	MinDiff	-18	-28	-24	-15	-17	-20	-17	-17	-21	-38	-20	-13	

Oslo
59.91 deg N
10.75 deg E

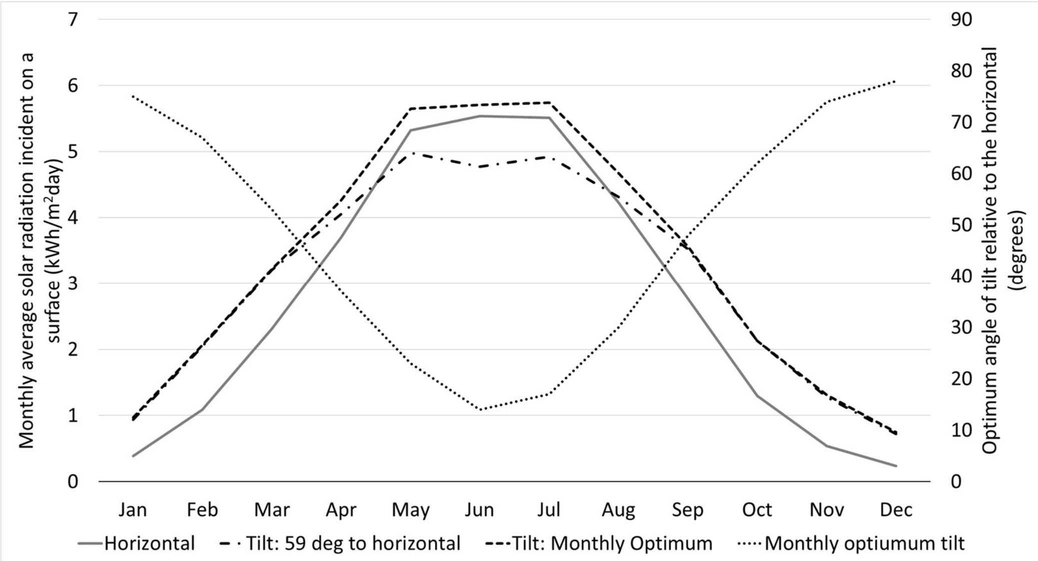
Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Av. Opt. Angle

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



[27] Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Seattle Insolation data[28]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	0.05	0.11	0.2	0.28	0.34	0.39	0.43	0.38	0.26	0.11	0.04	0.03	
	Average@03	n/a	0	0	0.02	0.05	0.08	0.08	0.04	0.01	0	n/a	n/a	
	Average@06	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@09	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@12	n/a	n/a	n/a	0	0	0.01	0.01	0	n/a	n/a	n/a	n/a	
	Average@15	0	0.01	0.05	0.13	0.2	0.23	0.23	0.17	0.11	0.04	0.01	0	
	Average@18	0.12	0.21	0.31	0.41	0.47	0.5	0.53	0.5	0.43	0.27	0.16	0.11	
	Average@21	0.19	0.28	0.39	0.47	0.54	0.56	0.62	0.6	0.5	0.32	0.2	0.16	
	MaxDiff	27	22	27	22	25	21	22	13	17	28	27	19	
	MinDiff	-17	-29	-20	-15	-14	-15	-30	-17	-14	-13	-17	-17	
	Daily Av Horz	1.11	1.96	2.97	4.07	4.98	5.49	5.86	5.23	4.05	2.31	1.26	0.94	3.36
	Daily Av 47de	1.7	2.81	3.54	4.17	4.57	4.78	5.23	5.21	4.71	3.15	1.97	1.53	3.62
	Daily Av Opt /	1.74	2.83	3.55	4.35	5.09	5.56	5.96	5.53	4.75	3.16	2.01	1.59	3.85
	Opt Ang	61	55	41	27	14	9	11	24	39	52	60	64	37.9
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	47 deg	1.5	1.4	1.2	1.0	0.9	0.9	0.9	1.0	1.2	1.4	1.6	1.6	
	Opt Ang	1.6	1.4	1.2	1.1	1.0	1.0	1.0	1.1	1.2	1.4	1.6	1.7	
47 deg														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Seattle	Average@00	0.076577	0.157704082	0.238384	0.28688	0.312008	0.339563	0.383771	0.378547	0.30237	0.15	0.06254	0.04883	
Seattle	Average@03	#VALUE!	0	0	0.020491	0.045884	0.069654	0.071399	0.039847	0.01163	0	#VALUE!	#VALUE!	
Seattle	Average@06	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Seattle	Average@09	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Seattle	Average@12	#VALUE!	#VALUE!	#VALUE!	0	0	0.008707	0.008925	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Seattle	Average@15	0	0.014336735	0.059596	0.133194	0.183534	0.200255	0.205273	0.16935	0.127926	0.054545	0.015635	0	
Seattle	Average@18	0.183784	0.301071429	0.369495	0.420074	0.431305	0.435337	0.47302	0.498088	0.500074	0.368182	0.250159	0.179043	
Seattle	Average@21	0.290991	0.401428571	0.464848	0.481548	0.495542	0.487577	0.553345	0.597706	0.581481	0.436364	0.312698	0.260426	
Seattle	MaxDiff	27	22	27	22	25	21	22	13	17	28	27	19	
Seattle	MinDiff	-17	-29	-20	-15	-14	-15	-30	-17	-14	-13	-17	-17	
Opt Ang														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	0.078378	0.158826531	0.239057	0.299263	0.34751	0.394973	0.437338	0.401797	0.304938	0.150476	0.06381	0.050745	
	Average@03	#VALUE!	0	0	0.021376	0.051104	0.08102	0.081365	0.042294	0.011728	0	#VALUE!	#VALUE!	
	Average@06	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@09	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@12	#VALUE!	#VALUE!	#VALUE!	0	0	0.010128	0.010171	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@15	0	0.014438776	0.059764	0.138943	0.204418	0.232933	0.233925	0.179751	0.129012	0.054719	0.015952	0	
	Average@18	0.188108	0.303214286	0.370539	0.438206	0.480382	0.506375	0.539044	0.528681	0.504321	0.369351	0.255238	0.186064	
	Average@21	0.297838	0.404285714	0.466162	0.502334	0.551928	0.56714	0.63058	0.634417	0.58642	0.437749	0.319048	0.270638	
	MaxDiff	27	22	27	22	25	21	22	13	17	28	27	19	
	MinDiff	-17	-29	-20	-15	-14	-15	-30	-17	-14	-13	-17	-17	

Seattle
47.61 deg N
122.33 deg W

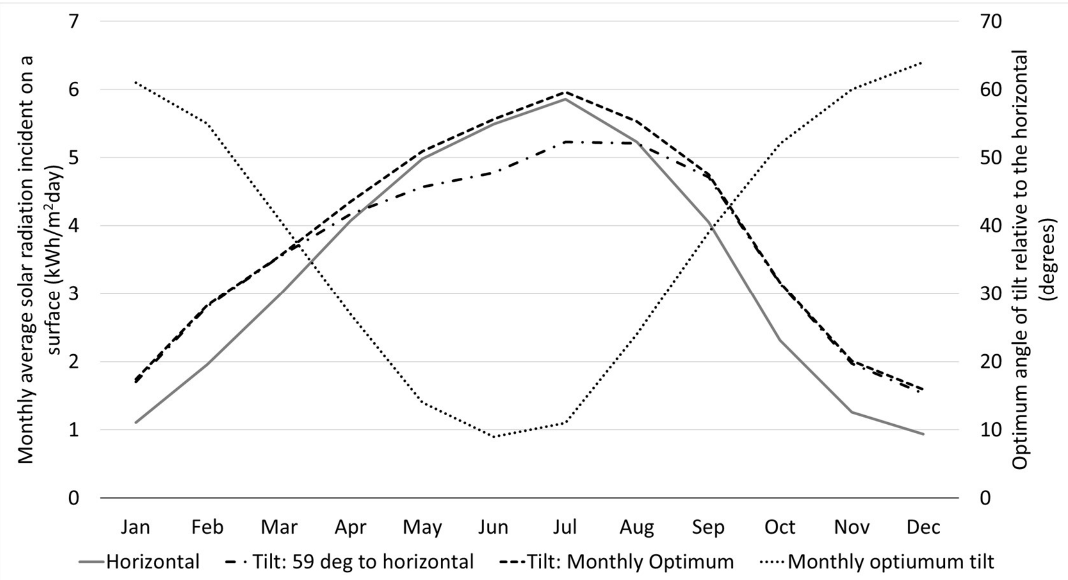
Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Av. Opt. Angle

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



[28] Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Carcassonne Insolation data[29]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@03	n/a	n/a	n/a	n/a	0	0	0	n/a	n/a	n/a	n/a	n/a	
	Average@06	0	0	0.03	0.07	0.13	0.15	0.13	0.1	0.05	0.02	0	0	
	Average@09	0.12	0.2	0.32	0.39	0.47	0.49	0.52	0.48	0.39	0.26	0.16	0.11	
	Average@12	0.25	0.35	0.48	0.53	0.6	0.64	0.69	0.65	0.54	0.36	0.26	0.22	
	Average@15	0.12	0.2	0.31	0.36	0.43	0.48	0.52	0.47	0.35	0.2	0.1	0.08	
	Average@18	0	0.01	0.02	0.05	0.09	0.13	0.13	0.08	0.03	0	0	n/a	
	Average@21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	MaxDiff	24	28	29	33	17	17	12	13	16	18	25	24	
	MinDiff	-26	-16	-26	-22	-18	-19	-20	-14	-11	-32	-20	-29	
	Daily Av Horz	1.52	2.36	3.56	4.34	5.31	5.88	6.16	5.48	4.24	2.6	1.63	1.29	3.7
	Daily Av 43de	2.62	3.38	4.37	4.46	4.87	5.12	5.49	5.42	4.9	3.54	2.6	2.35	4.1
	Daily Av Opt /	2.76	3.43	4.37	4.62	5.36	5.92	6.21	5.73	4.92	3.56	2.7	2.51	4.35
	Opt Ang	63	54	42	25	13	5	8	21	37	50	60	66	36.9
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	43 deg	1.7	1.4	1.2	1.0	0.9	0.9	0.9	1.0	1.2	1.4	1.6	1.8	
	Opt Ang	1.8	1.5	1.2	1.1	1.0	1.0	1.0	1.0	1.2	1.4	1.7	1.9	
43 deg														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Carcasson	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Carcasson	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Carcasson	Average@06	0	0	0.036826	0.071935	0.119228	0.130612	0.11586	0.098905	0.057783	0.027231	0	0	
Carcasson	Average@09	0.206842	0.286440678	0.392809	0.400783	0.431055	0.426667	0.463442	0.474745	0.450708	0.354	0.255215	0.200388	
Carcasson	Average@12	0.430921	0.501271186	0.589213	0.544654	0.550282	0.557279	0.614951	0.642883	0.624057	0.490154	0.414724	0.400775	
Carcasson	Average@15	0.206842	0.286440678	0.380534	0.369954	0.394369	0.417959	0.463442	0.464854	0.404481	0.272308	0.159509	0.145736	
Carcasson	Average@18	0	0.014322034	0.024551	0.051382	0.082542	0.113197	0.11586	0.079124	0.03467	0	0	#VALUE!	
Carcasson	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Carcasson	MaxDiff	24	28	29	33	17	17	12	13	16	18	25	24	
Carcasson	MinDiff	-26	-16	-26	-22	-18	-19	-20	-14	-11	-32	-20	-29	
Opt Ang														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@06	0	0	0.036826	0.074516	0.131224	0.15102	0.131055	0.104562	0.058019	0.027385	0	0	
	Average@09	0.217895	0.290677966	0.392809	0.415161	0.474426	0.493333	0.524221	0.501898	0.452547	0.356	0.265031	0.214031	
	Average@12	0.453947	0.508686441	0.589213	0.564194	0.60565	0.644354	0.695601	0.679653	0.626604	0.492923	0.430675	0.428062	
	Average@15	0.217895	0.290677966	0.380534	0.383226	0.434049	0.483265	0.524221	0.491442	0.406132	0.273846	0.165644	0.155659	
	Average@18	0	0.014533898	0.024551	0.053226	0.090847	0.130884	0.131055	0.08365	0.034811	0	0	#VALUE!	
	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	MaxDiff	24	28	29	33	17	17	12	13	16	18	25	24	
	MinDiff	-26	-16	-26	-22	-18	-19	-20	-14	-11	-32	-20	-29	

Carcassonne
43.21 deg N
2.35 deg E

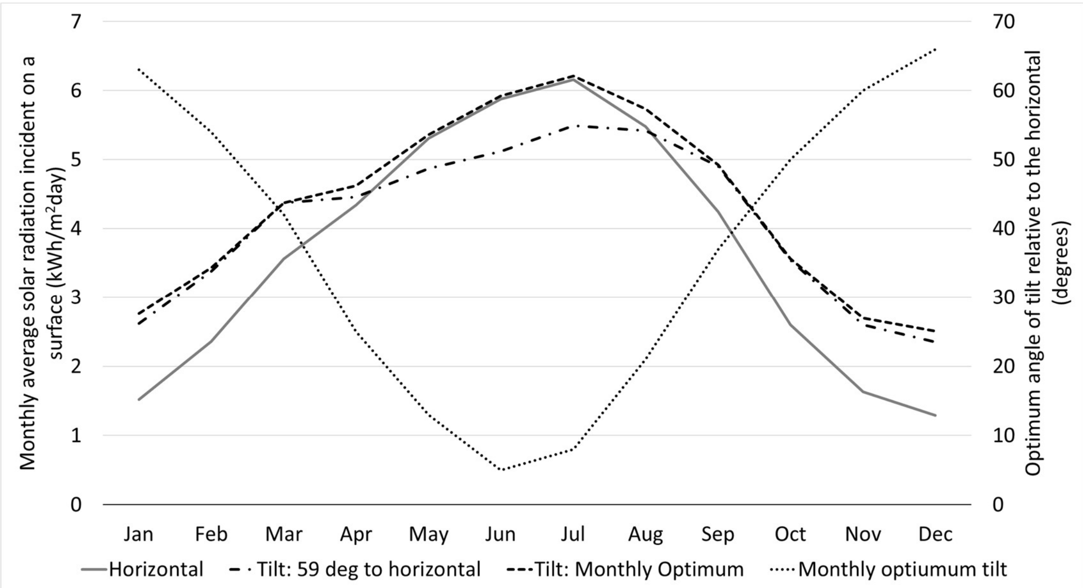
Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Av. Opt. Angle

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



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29 Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Athens Insolation data[30]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@03	n/a	n/a	0	0	0.01	0.02	0.01	0.01	0	0	n/a	n/a	
	Average@06	0.04	0.07	0.14	0.28	0.36	0.42	0.39	0.32	0.24	0.14	0.07	0.04	
	Average@09	0.3	0.38	0.5	0.62	0.72	0.82	0.81	0.77	0.65	0.48	0.33	0.26	
	Average@12	0.3	0.38	0.49	0.59	0.67	0.77	0.77	0.73	0.59	0.41	0.28	0.24	
	Average@15	0.05	0.1	0.16	0.23	0.28	0.37	0.37	0.31	0.2	0.08	0.03	0.02	
	Average@18	n/a	n/a	0	0	0.01	0.02	0.02	0.01	0	n/a	n/a	n/a	
	Average@21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	MaxDiff	26	22	26	14	16	7	8	7	14	19	23	28	
	MinDiff	-32	-21	-31	-17	-9	-16	-10	-9	-13	-19	-21	-24	
	Daily Av Horz	2.14	2.88	4	5.37	6.43	7.46	7.36	6.62	5.21	3.44	2.18	1.73	4.57
	Daily Av 37de	3.28	3.75	4.65	5.48	5.91	6.49	6.56	6.5	5.89	4.49	3.12	2.67	4.9
	Daily Av Opt /	3.48	3.82	4.65	5.63	6.46	7.41	7.34	6.82	5.9	4.55	3.24	2.84	5.19
	Opt Ang	59	49	37	22	9	4	6	17	33	47	55	60	33
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	37 deg	1.5	1.3	1.2	1.0	0.9	0.9	0.9	1.0	1.1	1.3	1.4	1.5	
	Opt Ang	1.6	1.3	1.2	1.0	1.0	1.0	1.0	1.0	1.1	1.3	1.5	1.6	

Athens
37.98 deg N
23.73 deg E

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

37 deg

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Athens	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Athens	Average@03	#VALUE!	#VALUE!	0	0	0.009191	0.017399	0.008913	0.009819	0	0	#VALUE!	#VALUE!
Athens	Average@06	0.061308	0.091145833	0.16275	0.285736	0.330886	0.365389	0.347609	0.314199	0.271324	0.182733	0.100183	0.061734
Athens	Average@09	0.459813	0.494791667	0.58125	0.6327	0.661773	0.713378	0.721957	0.756042	0.734837	0.626512	0.472294	0.401272
Athens	Average@12	0.459813	0.494791667	0.569625	0.602086	0.615816	0.669879	0.686304	0.716767	0.667006	0.535145	0.400734	0.370405
Athens	Average@15	0.076636	0.130208333	0.186	0.234711	0.257356	0.32189	0.329783	0.304381	0.226104	0.104419	0.042936	0.030867
Athens	Average@18	#VALUE!	#VALUE!	0	0	0.009191	0.017399	0.017826	0.009819	0	#VALUE!	#VALUE!	#VALUE!
Athens	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Athens	MaxDiff	26	22	26	14	16	7	8	7	14	19	23	28
Athens	MinDiff	-32	-21	-31	-17	-9	-16	-10	-9	-13	-19	-21	-24

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

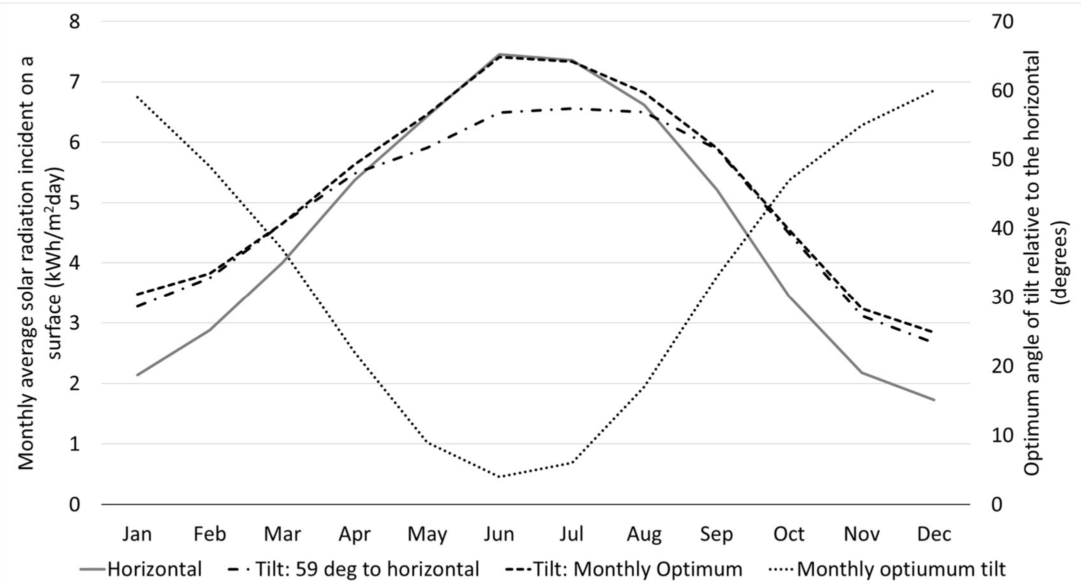
Av. Opt. Angle

Opt Ang

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	Average@03	#VALUE!	#VALUE!	0	0	0.010047	0.019866	0.009973	0.010302	0	0	#VALUE!	#VALUE!
	Average@06	0.065047	0.092847222	0.16275	0.293557	0.36168	0.417185	0.38894	0.329668	0.271785	0.185174	0.104037	0.065665
	Average@09	0.48785	0.504027778	0.58125	0.650019	0.723359	0.814504	0.807799	0.793263	0.736084	0.634884	0.490459	0.426821
	Average@12	0.48785	0.504027778	0.569625	0.618566	0.673126	0.764839	0.767908	0.752054	0.668138	0.542297	0.416147	0.393988
	Average@15	0.081308	0.132638889	0.186	0.241136	0.281306	0.36752	0.368995	0.319366	0.226488	0.105814	0.044587	0.032832
	Average@18	#VALUE!	#VALUE!	0	0	0.010047	0.019866	0.019946	0.010302	0	#VALUE!	#VALUE!	#VALUE!
	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	MaxDiff	26	22	26	14	16	7	8	7	14	19	23	28
	MinDiff	-32	-21	-31	-17	-9	-16	-10	-9	-13	-19	-21	-24

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



30 Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Mumbai Insolation data[31]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	n/a	n/a	0	0	0.01	0.01	0	0	0	0	0	n/a	
	Average@03	0.2	0.24	0.32	0.38	0.4	0.28	0.24	0.24	0.28	0.31	0.28	0.22	
	Average@06	0.7	0.79	0.87	0.91	0.88	0.69	0.61	0.64	0.73	0.76	0.74	0.69	
	Average@09	0.67	0.77	0.83	0.84	0.81	0.63	0.56	0.59	0.65	0.66	0.62	0.6	
	Average@12	0.15	0.21	0.25	0.25	0.27	0.21	0.19	0.17	0.16	0.12	0.09	0.1	
	Average@15	n/a	n/a	n/a	n/a	0	0	0	0	n/a	n/a	n/a	n/a	
	Average@18	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	MaxDiff	3	3	3	4	5	13	16	12	12	7	5	4	
	MinDiff	-3	-3	-5	-4	-9	-10	-15	-18	-16	-11	-6	-8	
	Daily Av Horz	5.32	6.25	7.05	7.38	7.33	5.64	5	5.12	5.65	5.72	5.38	5	5.89
	Daily Av 19de	6.54	7.17	7.43	7.14	6.72	5.63	4.94	4.85	5.69	6.29	6.46	6.13	6.24
	Daily Av Opt /	7.28	7.49	7.44	7.28	7.29	5.68	5	5.02	5.7	6.4	7.03	6.89	6.54
	Opt Ang	47	37	23	6	0	10	8	1	15	31	44	48	22.4
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	19 deg	1.2	1.1	1.1	1.0	0.9	1.0	1.0	0.9	1.0	1.1	1.2	1.2	
	Opt Ang	1.4	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.3	1.4	

Mumbai
19.08 deg N
72.88 deg E

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

19 deg

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mumbai	Average@00	#VALUE!	#VALUE!	0	0	0.009168	0.009982	0	0	0	0	0	#VALUE!
Mumbai	Average@03	0.245865	0.275328	0.337248	0.367642	0.366712	0.279504	0.23712	0.227344	0.281982	0.340892	0.336208	0.26972
Mumbai	Average@06	0.860526	0.906288	0.916894	0.880407	0.806767	0.688777	0.60268	0.60625	0.735168	0.835734	0.88855	0.84594
Mumbai	Average@09	0.823647	0.883344	0.874738	0.812683	0.742592	0.628883	0.55328	0.558887	0.654602	0.725769	0.744461	0.7356
Mumbai	Average@12	0.184398	0.240912	0.263475	0.24187	0.247531	0.209628	0.18772	0.161035	0.161133	0.131958	0.108067	0.1226
Mumbai	Average@15	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Mumbai	Average@18	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Mumbai	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Mumbai	MaxDiff	3	3	3	4	5	13	16	12	12	7	5	4
Mumbai	MinDiff	-3	-3	-5	-4	-9	-10	-15	-18	-16	-11	-6	-8

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

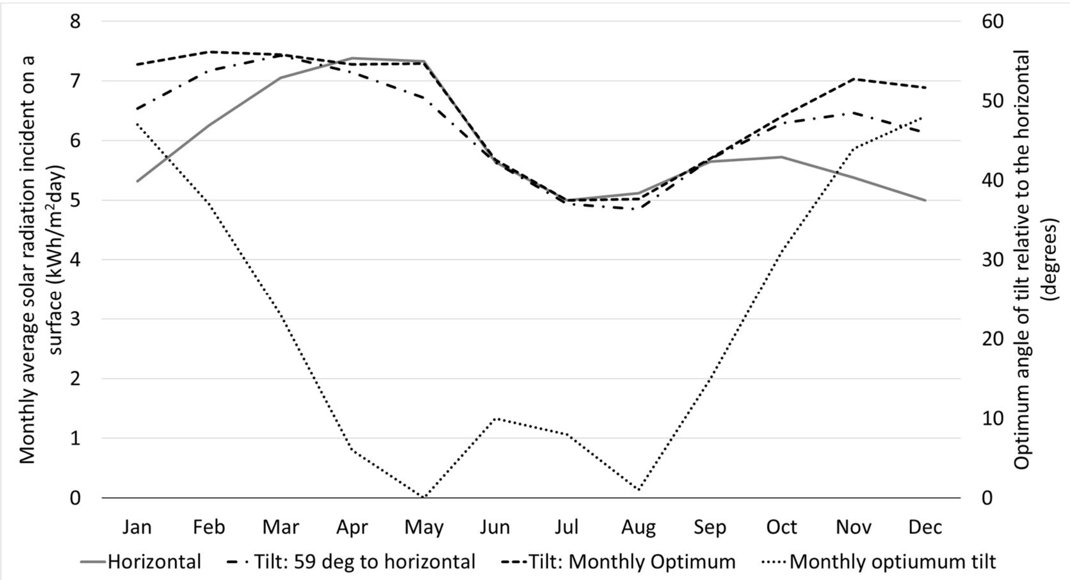
Av. Opt. Angle

Opt Ang

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Average@00	#VALUE!	#VALUE!	0	0	0.009945	0.010071	0	0	0	0	0	#VALUE!
	Average@03	0.273684	0.287616	0.337702	0.374851	0.397817	0.281986	0.24	0.235313	0.282478	0.346853	0.365874	0.30316
	Average@06	0.957895	0.946736	0.918128	0.897669	0.875198	0.694894	0.61	0.6275	0.73646	0.85035	0.966952	0.95082
	Average@09	0.916842	0.922768	0.875915	0.828618	0.80558	0.634468	0.56	0.578477	0.655752	0.738462	0.810149	0.8268
	Average@12	0.205263	0.251664	0.26383	0.246612	0.268527	0.211489	0.19	0.16668	0.161416	0.134266	0.117602	0.1378
	Average@15	#VALUE!	#VALUE!	#VALUE!	#VALUE!	0	0	0	0	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	Average@18	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	MaxDiff	3	3	3	4	5	13	16	12	12	7	5	4
	MinDiff	-3	-3	-5	-4	-9	-10	-15	-18	-16	-11	-6	-8

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



[31] Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Macapa Insolation data[32]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@03	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@06	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@09	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.03	0.03	0.02	
	Average@12	0.33	0.31	0.31	0.34	0.36	0.38	0.4	0.44	0.49	0.51	0.47	0.39	
	Average@15	0.59	0.56	0.59	0.6	0.57	0.61	0.66	0.72	0.79	0.78	0.72	0.65	
	Average@18	0.43	0.42	0.43	0.38	0.39	0.43	0.48	0.54	0.56	0.54	0.5	0.46	
	Average@21	0.06	0.06	0.06	0.04	0.04	0.05	0.06	0.07	0.06	0.05	0.04	0.05	
	MaxDiff	11	12	12	15	12	11	9	7	7	7	11	11	
	MinDiff	-14	-12	-11	-11	-12	-11	-9	-8	-8	-6	-13	-12	
	Daily Av Horz	4.36	4.25	4.3	4.29	4.32	4.59	5.01	5.49	5.99	5.89	5.42	4.84	4.9
	Daily Av 0deg	4.3	4.19	4.24	4.23	4.26	4.54	4.95	5.42	5.91	5.81	5.35	4.79	4.84
	Daily Av Opt /	4.51	4.26	4.25	4.25	4.36	4.75	5.17	5.51	5.92	5.9	5.65	5.14	4.98
	Opt Ang	21	13	2	7	15	20	19	13	2	12	22	26	14.3
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	0 deg	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	Opt Ang	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	
0 deg														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Macapa	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Macapa	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Macapa	Average@06	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
Macapa	Average@09	0.009862	0.009858824	0.00986	0.00986	0.019722	0.009891	0.00988	0.009872	0.019733	0.029593	0.029613	0.019793	
Macapa	Average@12	0.325459	0.305623529	0.305674	0.335245	0.355	0.375861	0.39521	0.43439	0.483456	0.503073	0.46393	0.385971	
Macapa	Average@15	0.581881	0.552094118	0.581767	0.591608	0.562083	0.603355	0.652096	0.71082	0.779449	0.769406	0.710701	0.643285	
Macapa	Average@18	0.424083	0.414070588	0.424	0.374685	0.384583	0.425316	0.474251	0.533115	0.552521	0.532666	0.493542	0.455248	
Macapa	Average@21	0.059174	0.059152941	0.059163	0.039441	0.039444	0.049455	0.059281	0.069107	0.059199	0.049321	0.039483	0.049483	
Macapa	MaxDiff	11	12	12	15	12	11	9	7	7	7	11	11	
Macapa	MinDiff	-14	-12	-11	-11	-12	-11	-9	-8	-8	-6	-13	-12	
Opt Ang														
Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@06	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
	Average@09	0.010344	0.010023529	0.009884	0.009907	0.020185	0.010349	0.010319	0.010036	0.019766	0.030051	0.031273	0.02124	
	Average@12	0.341353	0.310729412	0.306395	0.33683	0.363333	0.393246	0.412774	0.441603	0.484274	0.510866	0.489945	0.414174	
	Average@15	0.610298	0.561317647	0.58314	0.594406	0.575278	0.631264	0.681078	0.722623	0.780768	0.781324	0.750554	0.690289	
	Average@18	0.444794	0.420988235	0.425	0.376457	0.393611	0.444989	0.495329	0.541967	0.553456	0.540917	0.521218	0.488512	
	Average@21	0.062064	0.060141176	0.059302	0.039627	0.04037	0.051743	0.061916	0.070255	0.059299	0.050085	0.041697	0.053099	
	MaxDiff	11	12	12	15	12	11	9	7	7	7	11	11	
	MinDiff	-14	-12	-11	-11	-12	-11	-9	-8	-8	-6	-13	-12	

Macapa
0.04 deg N
51.07 deg W

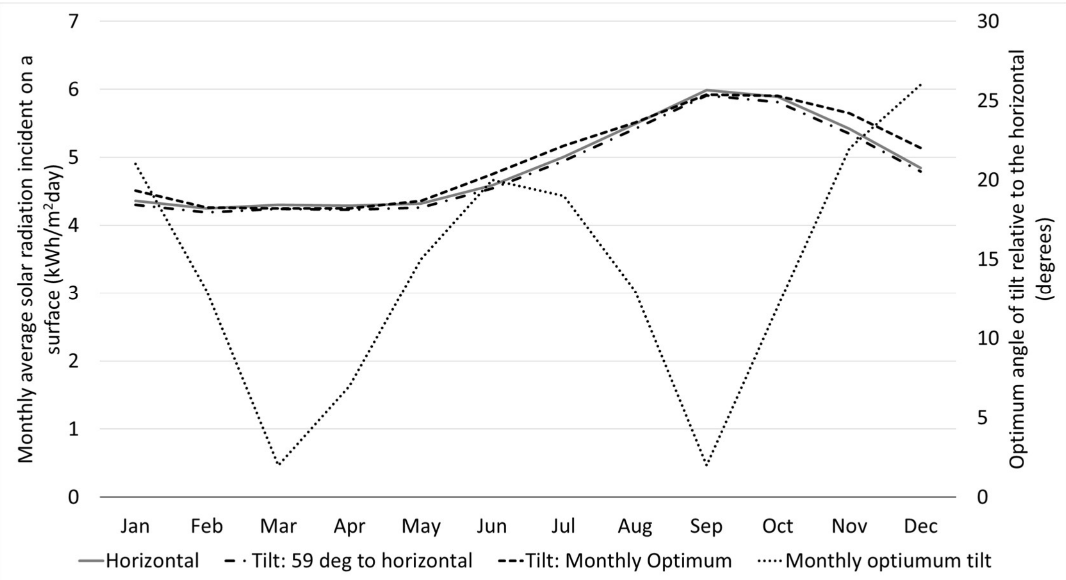
Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Av. Opt. Angle

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



32 Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Accra Insolation data[33]

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	Average@00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@03	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	Average@06	0.02	0.02	0.02	0.03	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.03	
	Average@09	0.4	0.41	0.44	0.47	0.44	0.37	0.36	0.36	0.39	0.45	0.46	0.43	
	Average@12	0.73	0.75	0.74	0.72	0.68	0.61	0.63	0.59	0.56	0.68	0.7	0.7	
	Average@15	0.5	0.52	0.51	0.47	0.42	0.38	0.42	0.42	0.43	0.41	0.4	0.45	
	Average@18	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.03	0.02	0.02	0.02	
	Average@21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
	MaxDiff	8	3	7	6	11	10	17	11	10	6	8	4	
	MinDiff	-8	-5	-7	-5	-7	-9	-15	-11	-12	-6	-6	-4	
	Daily Av Horz	5.24	5.4	5.41	5.36	4.97	4.43	4.58	4.44	4.48	4.95	5.01	5.03	4.93
	Daily Av 5deg	5.36	5.45	5.37	5.3	4.94	4.41	4.56	4.39	4.42	4.96	5.1	5.16	4.95
	Daily Av Opt /	5.77	5.59	5.37	5.3	4.98	4.46	4.6	4.4	4.42	5.01	5.38	5.64	5.07
	Opt Ang	30	20	8	5	13	15	14	7	2	15	27	32	15.6
Change from Horz		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	5 deg	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	Opt Ang	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	

Accra
5.60 deg N
0.19 deg W

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

5 deg

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Accra	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Accra	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Accra	Average@06	0.020458	0.020185185	0.019852	0.029664	0.039759	0.029865	0.029869	0.029662	0.029598	0.040081	0.040719	0.030775
Accra	Average@09	0.40916	0.413796296	0.436747	0.464739	0.437344	0.36833	0.358428	0.355946	0.384777	0.450909	0.468263	0.441113
Accra	Average@12	0.746718	0.756944444	0.734529	0.71194	0.675895	0.607246	0.627249	0.583356	0.5525	0.681374	0.712575	0.718091
Accra	Average@15	0.51145	0.524814815	0.506229	0.464739	0.417465	0.378284	0.418166	0.41527	0.424241	0.410828	0.407186	0.46163
Accra	Average@18	0.040916	0.04037037	0.039704	0.029664	0.029819	0.029865	0.039825	0.03955	0.029598	0.02004	0.020359	0.020517
Accra	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Accra	MaxDiff	8	3	7	6	11	10	17	11	10	6	8	4
Accra	MinDiff	-8	-5	-7	-5	-7	-9	-15	-11	-12	-6	-6	-4

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

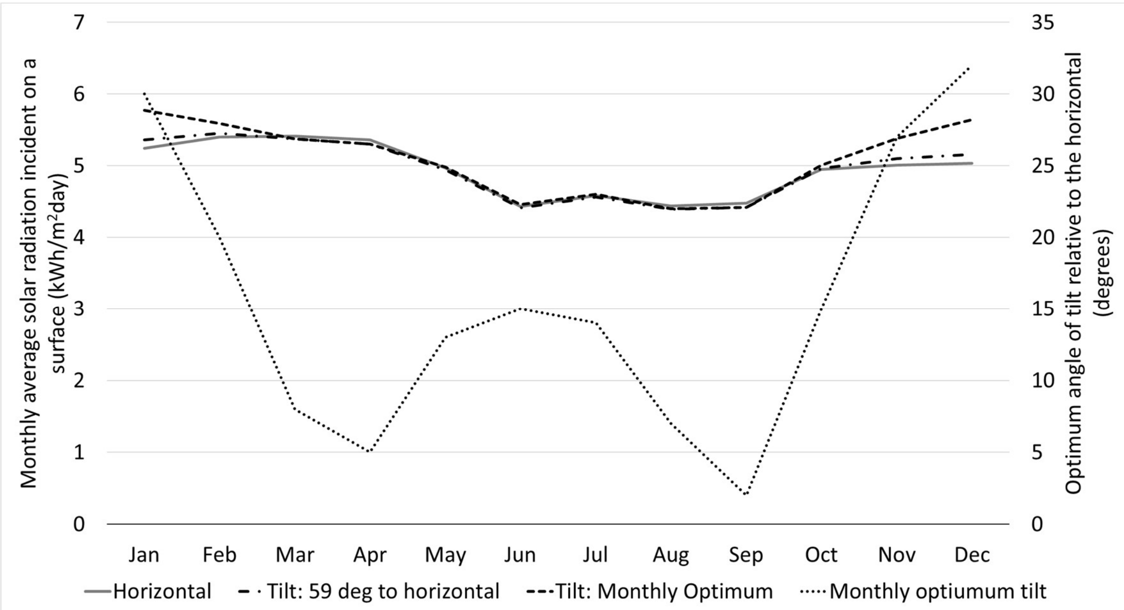
Av. Opt. Angle

Opt Ang

Location	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Average@00	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	Average@03	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	Average@06	0.022023	0.020703704	0.019852	0.029664	0.04008	0.030203	0.030131	0.02973	0.029598	0.040485	0.042954	0.033638
	Average@09	0.440458	0.424425926	0.436747	0.464739	0.440885	0.372506	0.361572	0.356757	0.384777	0.455455	0.493972	0.482147
	Average@12	0.803836	0.776388889	0.734529	0.71194	0.681368	0.614131	0.632751	0.584685	0.5525	0.688242	0.751697	0.784891
	Average@15	0.550573	0.538296296	0.506229	0.464739	0.420845	0.382573	0.421834	0.416216	0.424241	0.41497	0.429541	0.504573
	Average@18	0.044046	0.041407407	0.039704	0.029664	0.03006	0.030203	0.040175	0.03964	0.029598	0.020242	0.021477	0.022425
	Average@21	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
	MaxDiff	8	3	7	6	11	10	17	11	10	6	8	4
	MinDiff	-8	-5	-7	-5	-7	-9	-15	-11	-12	-6	-6	-4

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day)

Monthly Opt. Angle



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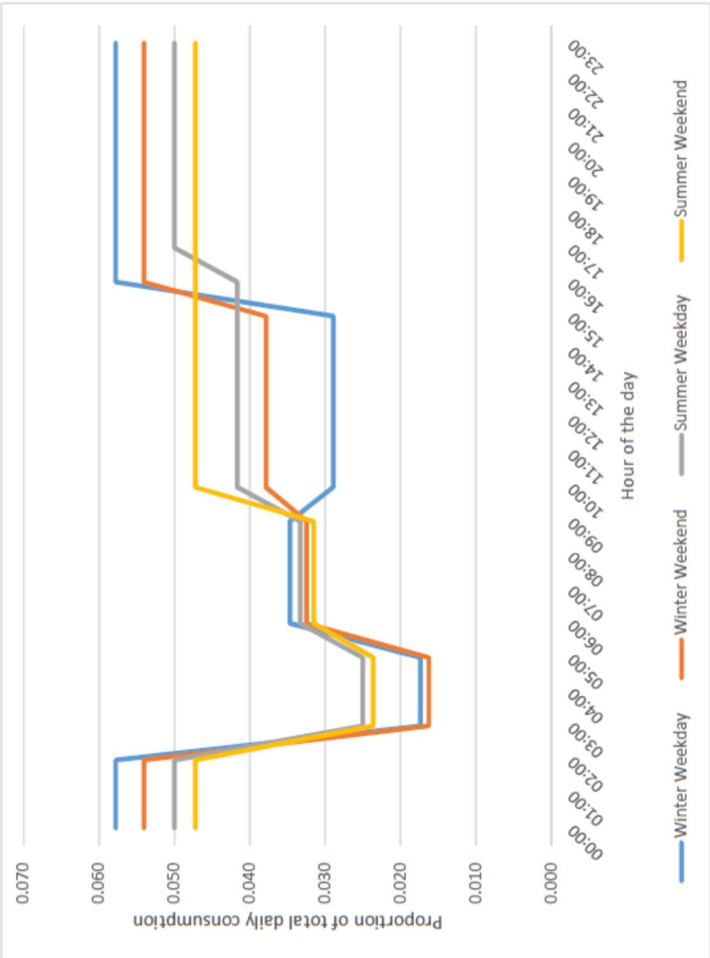
33 Based on data from:
NASA, n.d. *NASA Surface meteorology and Solar Energy.* [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

A49. Electricity demand profile data



Winter Weekday	Winter Weekend	Summer Weekday	Summer Weekend
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.017	0.016	0.025	0.024
0.017	0.016	0.025	0.024
0.017	0.016	0.025	0.024
0.035	0.032	0.033	0.031
0.035	0.032	0.033	0.031
0.035	0.032	0.033	0.031
0.035	0.032	0.033	0.031
0.029	0.038	0.042	0.047
0.029	0.038	0.042	0.047
0.029	0.038	0.042	0.047
0.029	0.038	0.042	0.047
0.029	0.038	0.042	0.047
0.029	0.038	0.042	0.047
0.058	0.054	0.042	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
0.058	0.054	0.050	0.047
1	1	1	1

A50. Electricity demands data[34]

Household Type	Average electricity use per person (kWh/a)	Average electricity use per person (kWh/day)	Winter WD	Winter WE	Summer WD	Summer WE
Single pensioner	3748	10	11.7	12.6	8.1	8.6
Single non-pensioner	3926	11	12.3	13.2	8.5	9.0
Multiple pensioner	1206	3	3.8	4.0	2.6	2.8
Household with children	1350	4	4.2	4.5	2.9	3.1
Multiple household with no dependents	1486	4	4.7	5.0	3.2	3.4

[34] Data from:
Energy Savings Trust, 2012. *Powering the Nation: Household electricity-using habits revealed,* London: Energy Savings Trust.

A51. Electricity heat gains data[35]

Household Type	Average heat gains per person (kWh/a)	Average heat gains per person (kWh/day)	Winter WD	Winter WE	Summer WD	Summer WE
Single pensioner	3181	9	10.0	10.7	6.9	7.3
Single non-pensioner	3315	9	10.4	11.1	7.2	7.6
Multiple pensioner	1014	3	3.2	3.4	2.2	2.3
Household with children	1128	3	3.5	3.8	2.5	2.6
Multiple household with no dependents	1261	3	4.0	4.2	2.7	2.9

[35] See Appendix A52 for the data used to calculate these values.

A52. Electricity demand details

Average no. people per household	Household Type	Average electricity use per person (kWh/a)	Average electricity use (kWh/a) per household: Washing machine	Clothes dryer	Dishwasher	Home computing	Lighting	Cold applicances	Cooking	Other kitchen	Consumer electronics	Total known	Unknown	Overall total
1	Single pensioner	3748	144	344	230	137	548	545	460	150	565	3123	625	3748
1	Single non-pensioner	3926	173	332	265	201	581	545	460	150	565	3272	654	3926
2.9	Multiple pensioner	1206	111	287	250	258	413	545	460	150	441	2915	583	3498
2.9	Household with children	1350	170	342	313	241	477	545	460	150	565	3263	653	3916
2.9	Multiple household with no dependents	1486	178	497	315	267	548	545	460	150	630	3590	718	4308

Household Type	Average heat gains per person (kWh/a)	Average internal heat gains from appliances per household (kWh/a): Washing machine	Clothes dryer	Dishwasher	Home computing	Lighting	Cold applicances	Cooking	Other kitchen	Consumer electronics	Total known	Unknown	Overall total
	Interior heat availaility factor	0.3	1	0.3	1	1	1	0.5	0.5	1		1	
Single pensioner	3181	43	344	69	137	548	545	230	75	565		625	3181
Single non-pensioner	3315	52	332	80	201	581	545	230	75	565		654	3315
Multiple pensioner	1014	33	287	75	258	413	545	230	75	441		583	2940
Household with children	1128	51	342	94	241	477	545	230	75	565		653	3273
Multiple household with no dependents	1261	53	497	95	267	548	545	230	75	630		718	3658

Dwelling type	Annual consumption (kWh/year)
Terraced house – mid-terrace	2,779
Terraced house – end-terrace	3,442
Terraced house – small up to 70m2	2,894
Terraced house – med/large over 70m2	4,399
Semi-detached house	3,847
Detached house	4,153
Bungalow	3,866
Flat	2,829
Weighted average of all households	**3,638**

Table 2. Annualised average electricity consumption (kWh/year) excluding primary electric heating

Powering the Nation
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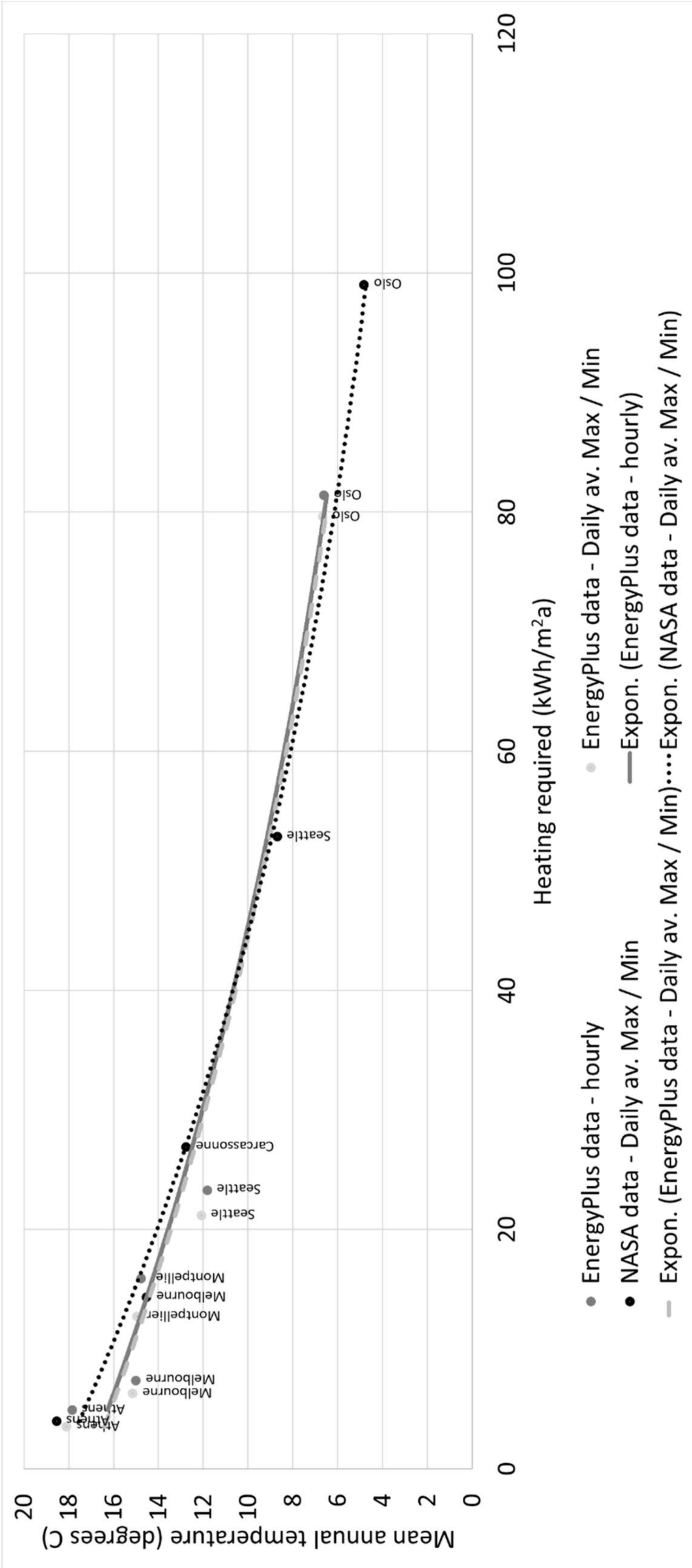
ISO 13790
Internal heat gains, heat gains from internal heat sources, including negative heat gains (dissipated heat from internal environment to cold sources or "sinks"), consist of any heat generated in the conditioned space by internal sources other than the energy intentionally utilized for space heating, space cooling or hot water preparation.
The internal heat gains include:
– metabolic heat from occupants and dissipated heat from appliances;
– heat dissipated from lighting devices;
– heat dissipated from, or absorbed by, hot and mains water and sewage systems;
– heat dissipated from, or absorbed by, heating, cooling and ventilation systems;
– heat from or to processes and goods.

A53. Comparison of SBM outputs using external temperature data inputs from NASA (average daily max./min.) and EnergyPlus (hourly and average daily max./min.)



A54. SBM validation output

Output: SBM based on UK Building Regulations

21/08/17 21:19 MATLAB Command Window 1 of 4

```
>> logDataExample
Enter location value: 10
2 - Material: Brick = 1, Straw Seq = 2, Straw exSeq = 3
Enter material value: 1
3 - Boundary: Operational only = 1, Operational+Embodied = 2
Enter boundary value: 2
4 - Balance Period: Annual = 1, Monthly = 2
Enter balance period value: 1
5 - PV Location: Onsite = 1, Remote = 2
Enter PV location value: 1
6 - Infiltration: 0.6ach+MVHR = 1, 10ach+MVHR = 2, 30m3 = 3
Enter infiltration value: 2
7 - Occupant Density: No people = 1, 35m2/p = 2, 20m2/p = 3
Enter occupant density value: 2
8 - PV Specification: LowE = 1, HighE = 2
Enter PV specification value: 1
OpE (kWh/m2a): 132.4929
OpC (kgCO2e/m2a): 40.1185
PV gen. (kWh/m2a): 58.789
PV gen. (kgCO2e/m2a): 30.5115
Internal floor area of building (m2):
         70.63

PV output (kWh/m2a): 58.789
CO2 from PV output (kgCO2e/m2a): 30.5115
PV EC (kgCO2e/m2a): 3.1646
PV EE (kWh notprimary/m2a): 5.1185
MVHR EC (kgCO2e/m2a): 0
Heating system EC (kgCO2e/m2a): 0.79639
Net PV benefit (kgCO2e/m2PVa): 42.9199
Total thermal energy loss (kWh/m2a): 138.0083
CO2 from thermal energy loss (kgCO2e/m2a): 29.8098
PV to balance thermal energy loss (m2): 49.0527
Total domestic heat gains (kWh/m2a): 48.8803
CO2 from domestic heat gains (kgCO2e/m2a): 10.5581
Total heating required (kWh/m2a): 94.5391
```

Output: SBM based on the Passivhaus Standard

```
>> logDataExample
Enter location value: 10
2 - Material: Brick = 1, Straw Seq = 2, Straw exSeq = 3
Enter material value: 1
3 - Boundary: Operational only = 1, Operational+Embodied = 2
Enter boundary value: 2
4 - Balance Period: Annual = 1, Monthly = 2
Enter balance period value: 1
5 - PV Location: Onsite = 1, Remote = 2
Enter PV location value: 1
6 - Infiltration: 0.6ach+MVHR = 1, 10ach+MVHR = 2, 30m3 = 3
Enter infiltration value: 1
7 - Occupant Density: No people = 1, 35m2/p = 2, 20m2/p = 3
Enter occupant density value: 2
8 - PV Specification: LowE = 1, HighE = 2
Enter PV specification value: 1
OpE (kWh/m2a): 65.7203
OpC (kgCO2e/m2a): 25.6956
PV gen. (kWh/m2a): 57.9351
PV gen. (kgCO2e/m2a): 30.0683
Internal floor area of building (m2):
         71.63

PV output (kWh/m2a): 57.9351
CO2 from PV output (kgCO2e/m2a): 30.0683
PV EC (kgCO2e/m2a): 3.1201
PV EE (kWh notprimary/m2a): 5.0466
MVHR EC (kgCO2e/m2a): 3.3
Heating system EC (kgCO2e/m2a): 0
Net PV benefit (kgCO2e/m2PVa): 42.8969
Total thermal energy loss (kWh/m2a): 66.4056
CO2 from thermal energy loss (kgCO2e/m2a): 14.3436
PV to balance thermal energy loss (m2): 23.952
Total domestic heat gains (kWh/m2a): 48.8803
CO2 from domestic heat gains (kgCO2e/m2a): 10.5581
Total heating required (kWh/m2a): 27.7665
```

A55. Example SBM heating and electricity demand profiles

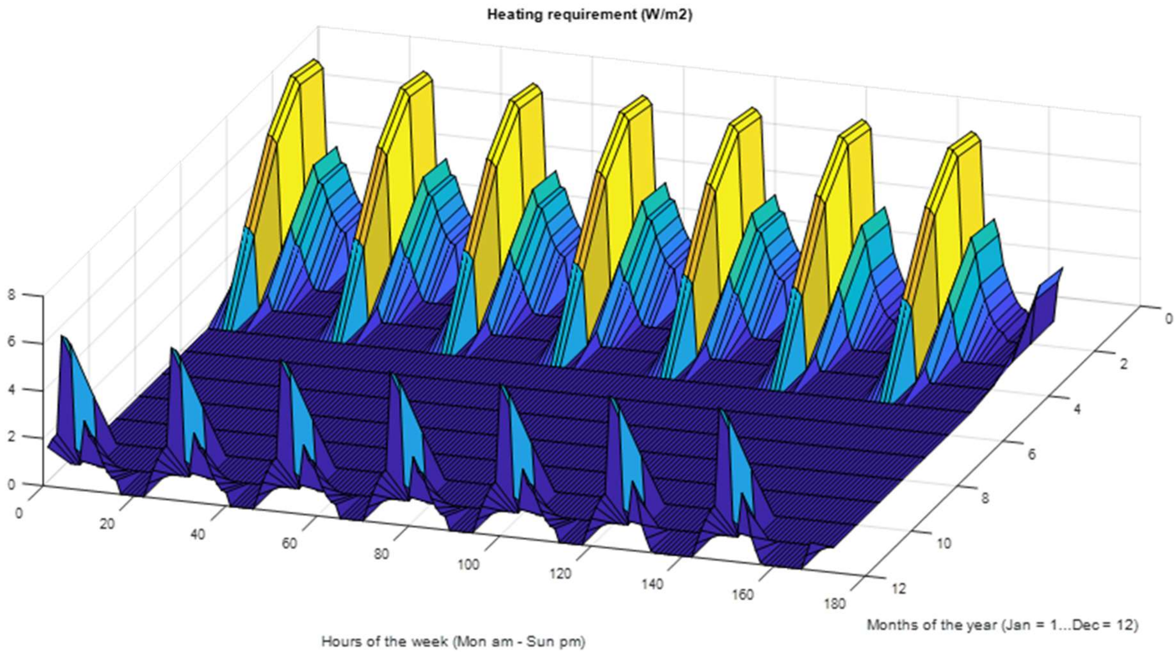


Figure 78: Hourly heating requirement to keep a house-sized building, located in Athens, heated to 20 °C. Glazing U-value = 0.8 W/m^{2}K. Infiltration levels as required for Passivhaus standard with MVHR present.

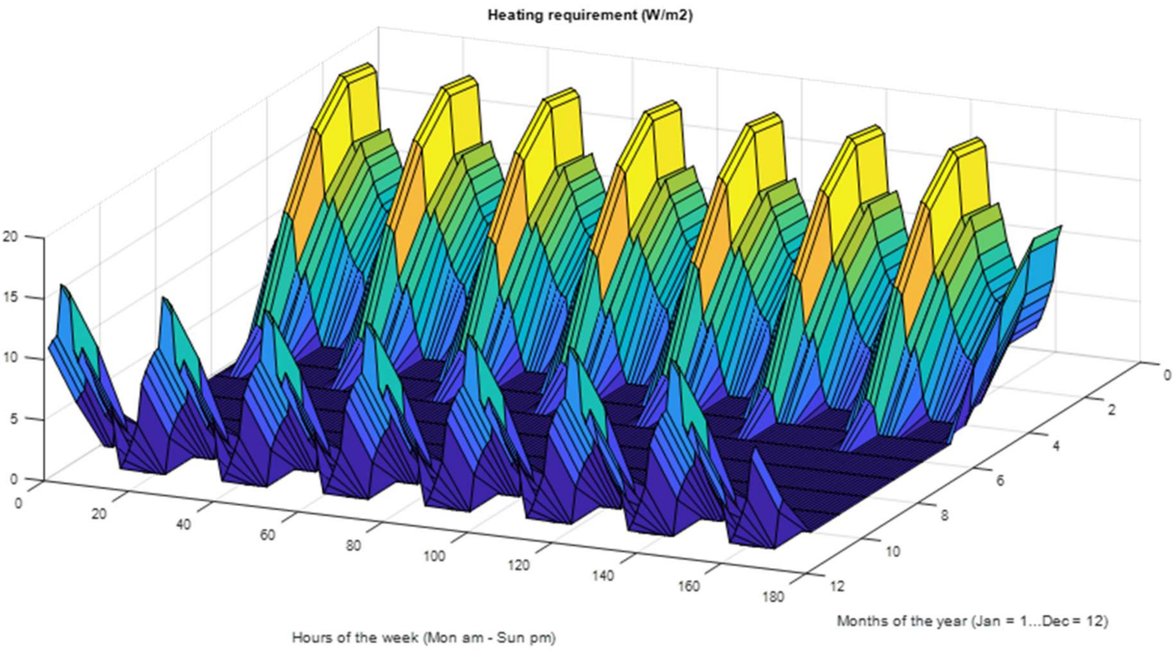


Figure 79: Hourly heating requirement to keep a house-sized building, located in Athens, heated to 21 °C. Glazing U-value = 1.4 W/m^{2}K. Infiltration levels as required for UK Building Regulations.

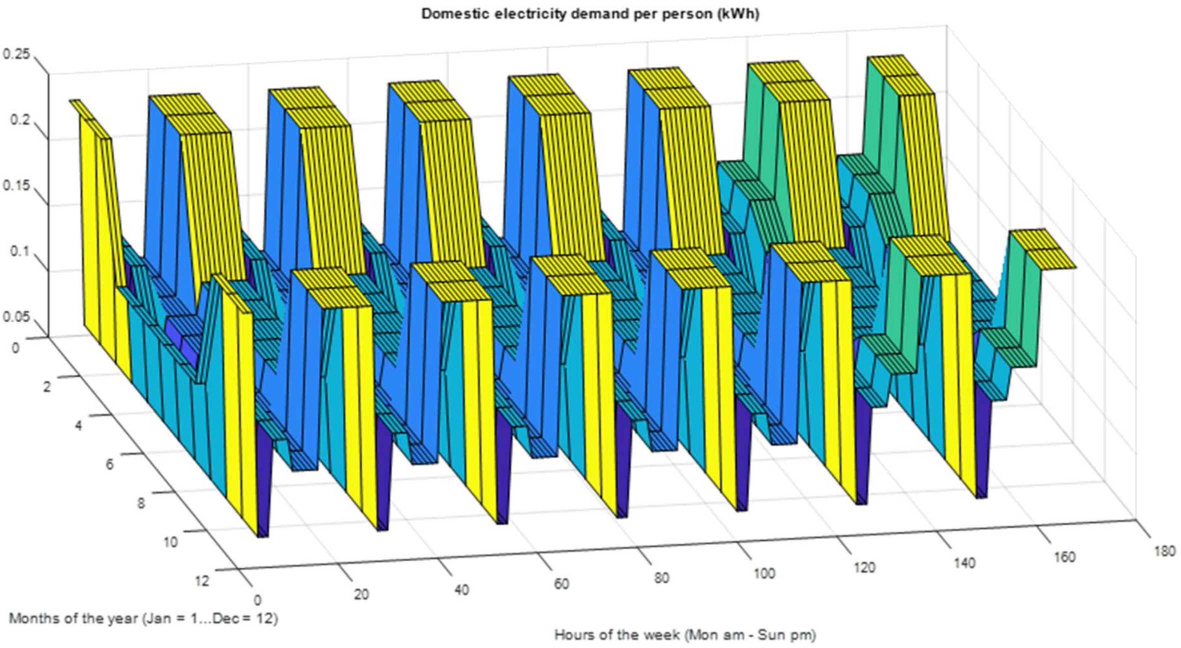


Figure 80: Hourly electricity demand profile for each occupant. This is always the same regardless of location.

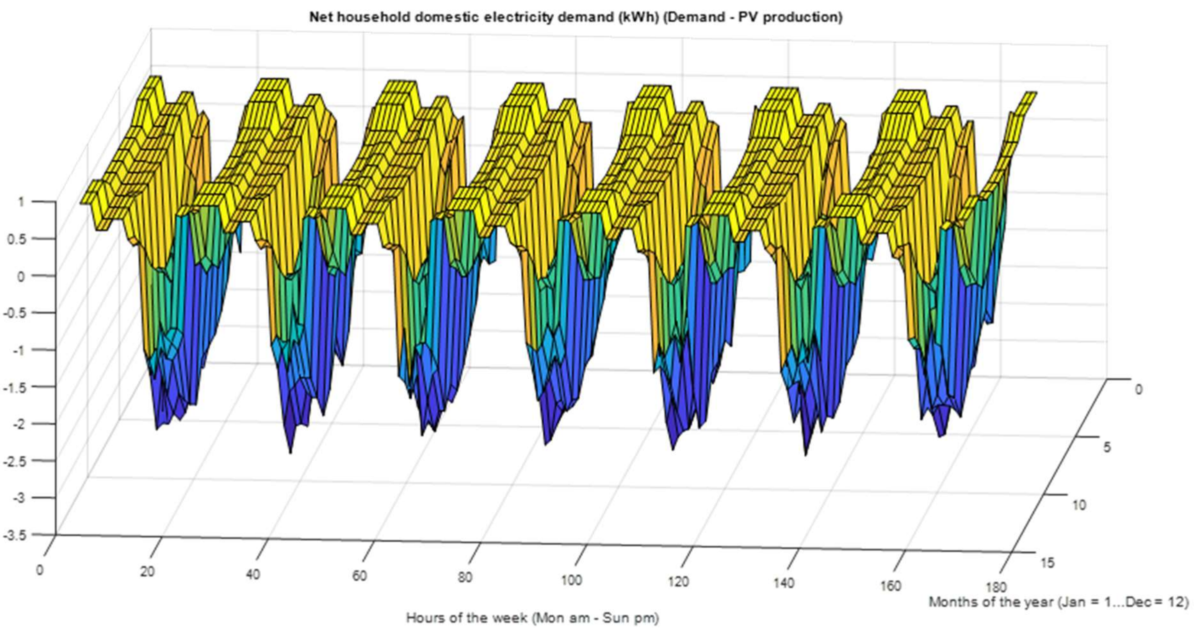


Figure 81: Hourly net electricity demand profile taking into account PV generation for a house-sized building located in Athens.

A56. SBM data import construction element details for Montgomery Primary School, Exeter[36]

External Walls

Material from MaterialProperties list	Depth (m)	Thermal Conductivity (W/mK)	EC per m^2 $kgCO_2$	EE per m^2 (MJ)
Concrete (general) 28/35 MPa	0.018	**1.3**	**4.0**	**29.5**
Polyurethane Rigid Foam	0.15	**0.023**	**15.7**	**456.8**
Concrete (general) 28/35 MPa	0.018	**1.3**	**4.0**	**29.5**

Ground floor

Material from MaterialProperties list	Depth (m)	Thermal Conductivity (W/mK)	EC per m^2 ($kgCO_2$)	EE per m^2 (MJ)
Concrete (general) 28/35 MPa	0.19	**1.3**	**42.6**	**311.6**
Expanded Polystyrene	0.185	**0.035**	**11.8**	**409.8**
High Density Polyethylene (HDPE) Resin	0.001	**0.5**	**1.5**	**75.2**
Sand	0.05	**2**	**0.5**	**8.9**
General aggregate (gravel or crushed rock)	0.6	**1.3**	**6.5**	**111.6**

Roof

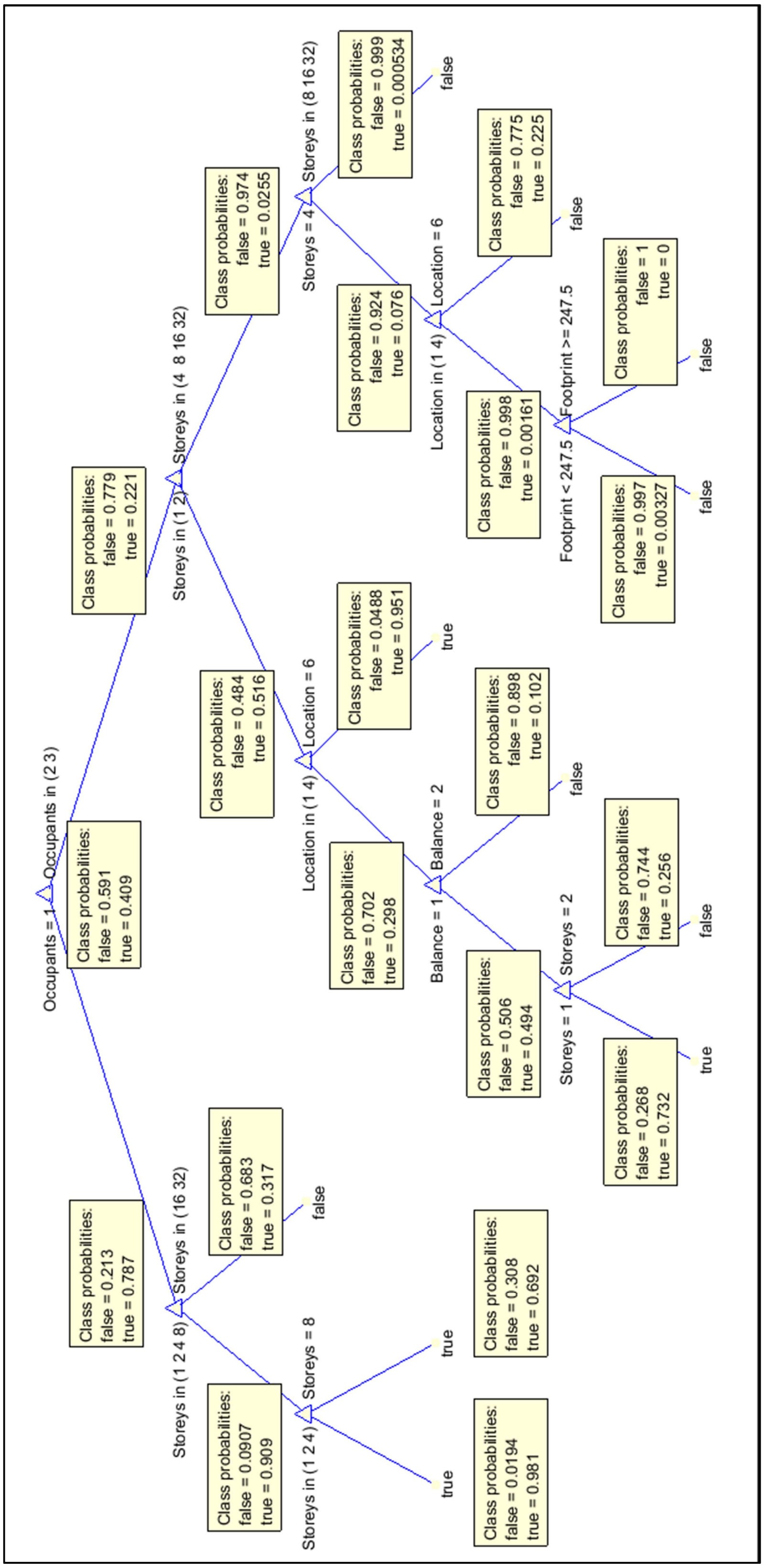
Material from MaterialProperties list	Depth (m)	Thermal Conductivity (W/mK)	EC per m^2	EE per m^2 (MJ)
Sawn softwood	0.036	**0.13**	**12.7368**	**162.504**
Polyurethane Rigid Foam	0.22	**0.023**	**22.968**	**669.9**

Windows

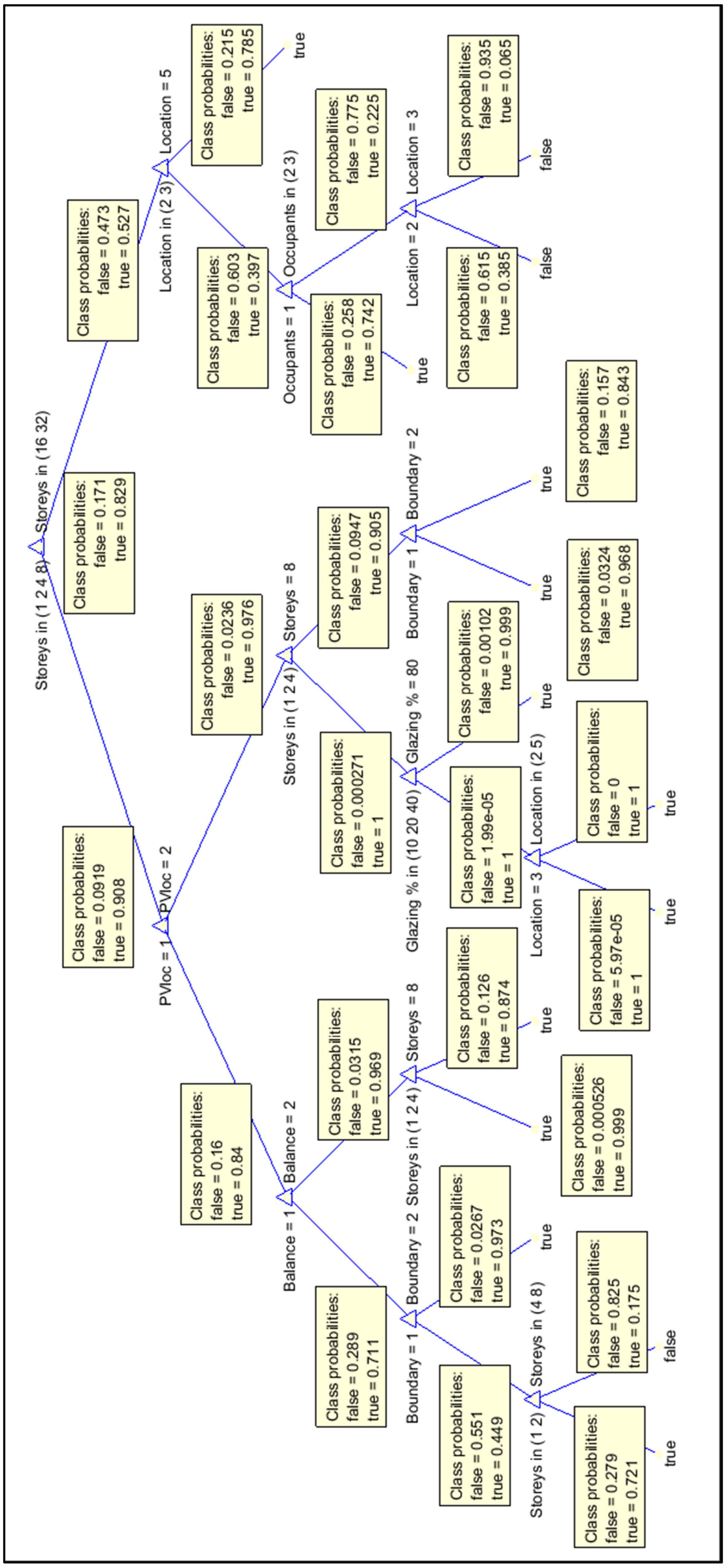
	Height (m)	Width (m)	Number	U-value	EC (kgCO2/unit)	EE (MJ/unit)	Total surface area (m^2)	Total EE (MJ)
Aluminium	1.2	1.2	550	0.8	1427.8	8640	**792.0**	**4752000**

[36] MaterialProperties list as in the Virtual Building Model – see Appendix A8.

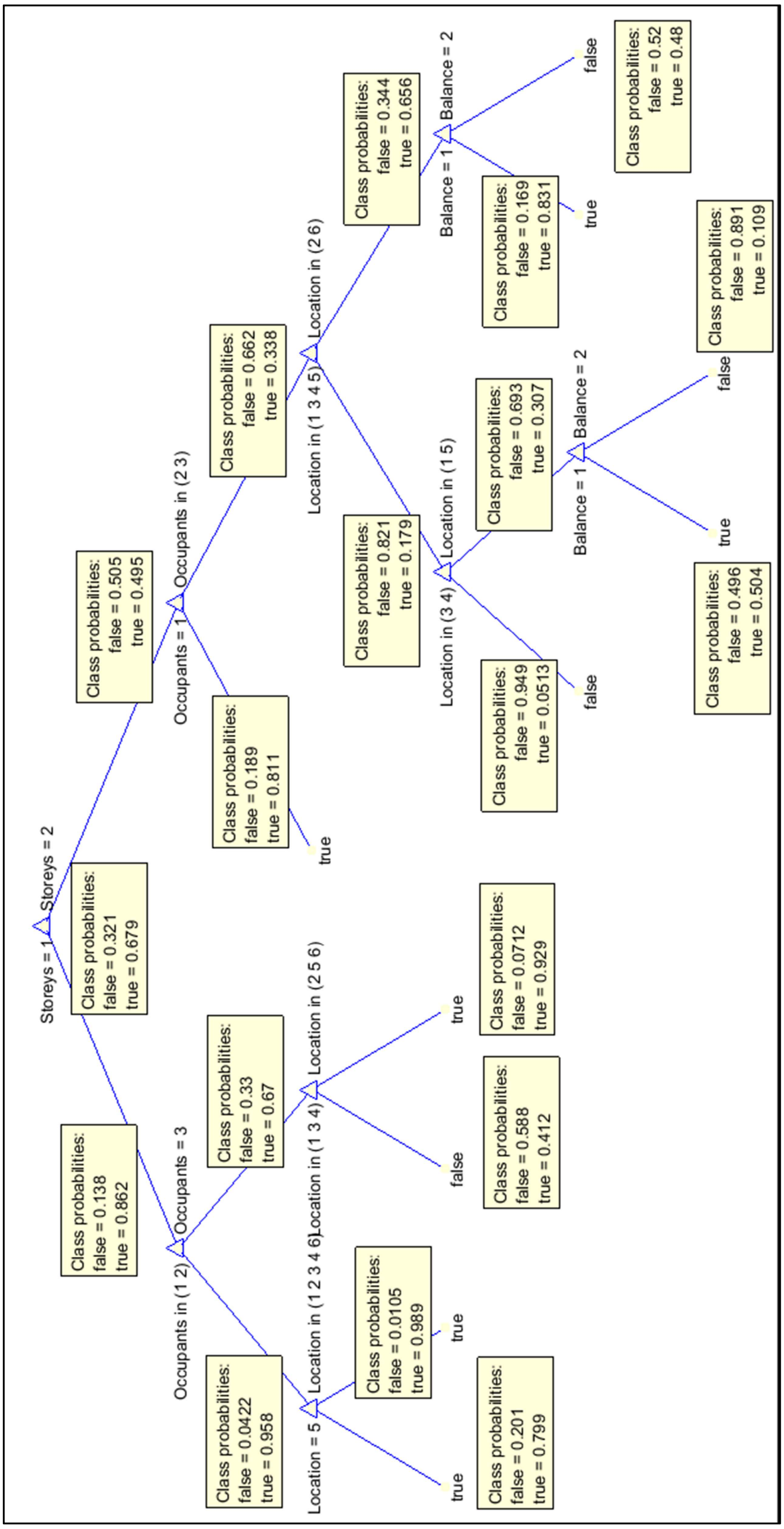
A57. ZCB Classification Tree – left branch



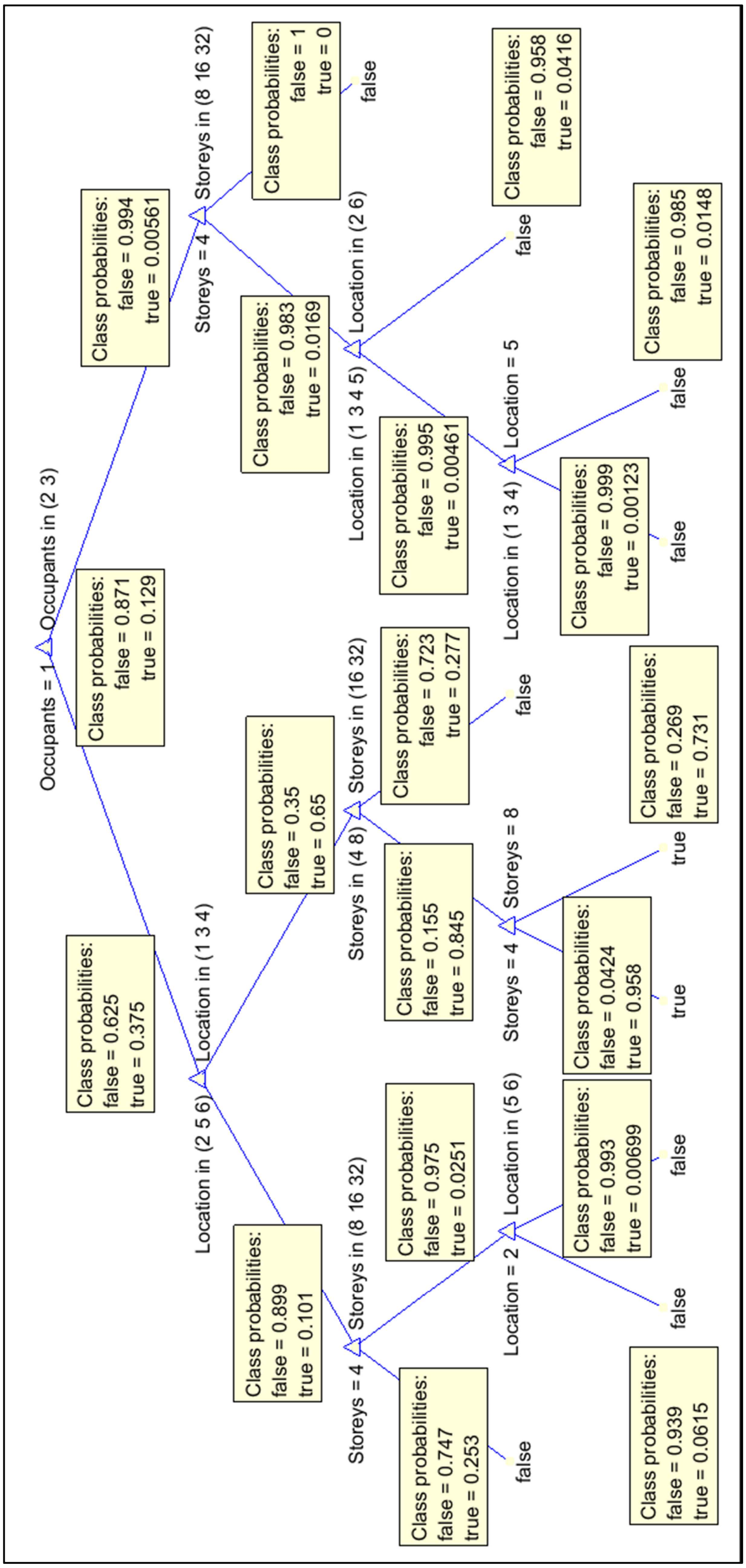
A58. ZCB Classification Tree – right branch



A59. ZEB Classification Tree – left branch



A60. ZEB Classification Tree – right branch



A61. Ranking of classification tree features

Carbon classification tree features						
Feature	**Branch level**	**(Branch level)^-1**		**Feature**	**sum(Branch level)^-1**	**Rank**
Location	1	1.00		Location	2.15	2
Occupants	2	0.50		Occupants	0.75	3
Height	3	0.33		Height	2.45	1
Location	4	0.25		Balance	0.45	4
Balance	5	0.20		PV location	0.33	6
Height	6	0.17		Boundary	0.40	5
Height	3	0.33		Footprint	0.17	8
Height	4	0.25		Glazing	0.20	7
Height	2	0.50				
Location	3	0.33				
Occupants	4	0.25				
Location	5	0.20				
PV location	3	0.33				
Balance	4	0.25				
Boundary	5	0.20				
Height	6	0.17				
Height	4	0.25				
Location	5	0.20				
Footprint	6	0.17				
Height	4	0.25				
Boundary	5	0.20				
Glazing	5	0.20				
Location	6	0.17				
Height	5	0.20				
Energy classification tree features						
Feature	**Branch level**	**(Branch level)^-1**		**Feature**	**sum(Branch level)^-1**	**Rank**
Height	1	1.00		Height	2.53	1
Height	2	0.50		Occupants	1.17	3
Occupants	3	0.33		Location	1.93	2
Location	4	0.25		Balance	0.37	4
Balance	5	0.20				
Location	5	0.20				
Balance	6	0.17				
Occupants	3	0.33				
Location	4	0.25				
Occupants	2	0.50				
Location	3	0.33				
Height	4	0.25				
Height	5	0.20				
Height	4	0.25				
Location	4	0.25				
Height	3	0.33				
Location	4	0.25				
Location	5	0.20				
Location	5	0.20				

A62. Antecedents returning a consequent maximum zero building proportion of 10 %

Consequent: 10 % ZCB max.

Antecedent				
Rule 1	Rule 2	Rule 3	Rule 4	SBM design space (million buildings)
High electricity grid CI (see Figure 30)	The number of storeys is greater than two (Storeys = 4, 8, 16, 32)	Building assessment assumes some occupants (Occupants = 2, 3)	n/a	**4.8** (4,822,682)
Low electricity grid CI (see Figure 30)	The number of storeys is greater than eight (Storeys = 16, 32)	As above	Buildings located in Macapa (Location = 3)	**0.6** (566,784)

Consequent: 10 % ZEB max.

Antecedent				
Rule 1	Rule 2	Rule 3	Rule 4	SBM design space (million buildings)
Short buildings (see Figure 31)	Building assessment assumes some occupants (Occupants = 2, 3)	The number of storeys is two (Storeys = 2)	Buildings located in hot climates (Location = 3, 4; average mean annual temperature: 27 °C)	**1.1** (1,092,096)
Tall buildings (see Figure 31)	Building assessment assumes no occupants (Occupants = 1)	The number of storeys is greater than four (Storeys = 8, 16, 32)	Buildings located in cooler climates (Location = 2, 5, 6; average mean annual temperature: 9 °C)	**1.7** (1,655,424)
	Building assessment assumes some occupants (Occupants = 2, 3)			**9.9** (9,897,984)

A63. Average occupancy densities for different countries

Country	**Average Floor space (m^2)[37]**	**Average Household size (No. members)[38]**	**Average Occupancy density (m^2/person)**
Canada	150	2.3	65
USA	130.7	2.6	50
Italy	108.2	2.4	45
Germany	92.2	2.1	44
New Zealand	114.7	2.7	42
Wales	83	2.3	36
Spain	91.2	2.6	35
Australia	86.8	2.5	35
France	79.6	2.3	35
Scotland	75.6	2.3	33
Northern Ireland	73.5	2.3	32
England	71.2	2.3	31
China	43.6	3.1	14
Hong Kong	32.9	2.9	11

37 Find Me A Floor, 2019. *Where in the world do you get the biggest home? An average floor space analysis*. [Online] Available at: https://www.findmeafloor.co.uk/where-in-the-world-do-you-get-the-biggest-home [Accessed 17 August 2019].

38 United Nations, 2017. *Household Size and Composition Around the World 2017: Data Booklet*. [Online] Available at: https://www.un.org/en/development/desa/population/publications/pdf/ageing/household_size_and_composition_around_the_world_2017_data_booklet.pdf [Accessed 17August 2019].